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# Satellite Power Systems (SPS) Concept Definition Study

## Volume III - Experimental Verification Definition

G. M. Hanley

CONTRACT NAS8-32475
SEPTEMBER 1980

NASA

142

NASA Contractor Report 3320

# Satellite Power Systems (SPS) Concept Definition Study

## Volume III - Experimental Verification Definition

G. M. Hanley
*Rockwell International*
*Downey, California*

Prepared for
Marshall Space Flight Center
under Contract NAS8-32475

National Aeronautics
and Space Administration

**Scientific and Technical**
**Information Branch**

1980

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# FOREWORD

This is Volume III - *Experimentation/Verification Element Definition*, of the SPS Concept Definition Study final report as submitted by Rockwell International through the Satellite Systems Division. All work was completed in response to the NASA/MSFC Contract NAS8-32475, Exhibit C, dated March 28, 1978.

The SPS final report will provide the NASA with additional information on the selection of a viable SPS concept and will furnish a basis for subsequent technology advancement and verification activities. Other volumes of the final report are listed as follows:

| Volume | Title |
|---|---|
| I | Executive Summary |
| II | Systems Engineering |
| IV | Transportation Analyses |
| V | Special Emphasis Studies |
| VI | In-Depth Element Investigations |
| VII | Systems/Subsystems Requirements Data Book |

The SPS Program Manager, G. M. Hanley, may be contacted on any of the technical or management aspects of this report. He may be reached at 213/594-3911, Seal Beach, California.

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# 1.0 SPS DEVELOPMENT PLANNING OVERVIEW

## 1.1 DEVELOPMENT PLANNING OBJECTIVES AND CONSIDERATIONS

A DOE task group was established in 1976 to evaluate the potential for the Solar Power Satellite System, including programmatic evaluation of program planning options. A guideline was established that programmatic decisions and development planning alternatives should be based upon a high-risk approach since launch vehicle and orbital operational questions would not be resolved.

More recently, DOE has proposed, for FY 1980 implementation, a modest environmentally oriented microwave technology exploratory research program aimed at reducing the uncertainty associated with microwave power system critical technical issues. These factors lead to the underlying premise that heavily funded, dedicated SPS development effort during the next five years or so is increasingly unlikely, and that a low-level step-by-step evolutionary approach to SPS development planning is realistic. This premise then dictates a planning logic that builds upon on-going and planned ground and space test activities--activities that can result in cost-effective SPS developmental progress if they can be focused to achieve significant advancement of SPS technology while also providing other planned benefits.

Based upon this background, an evolutionary SPS development plan was prepared to satisfy the objectives shown in Table 1.1-1. Planning analysis was directed toward the evolution of a scenario that met the stated objectives, was technically possible and economically attractive, and took into account constraining considerations, such as (1) requirements for very large-scale end-to-end demonstration in a compressed time frame, (2) the relative cost/technical merits of ground testing versus space testing, and (3) the need for large mass flow capability to LEO and GEO at reasonable cost per pound.

## 1.2 SPS DEVELOPMENT PLAN ELEMENTS

The principal elements of the SPS development plan are summarized in Figure 1.2-1. The Technology Advancement Phase consists of three major test elements.

- Microwave Ground Exploratory Research Program
- Key Technology Program (other than microwave)
- SPS Orbital Test Platform Demonstration Plan

Each of these test phases is discussed in detail in Section 2 - Technology Advancement Plan.

*Table 1.1-1. SPS Development Planning Objectives*

STRUCTURE A SYNTHESIZED SPS DEVELOPMENT PLAN THAT REFLECTS THESE CONSIDERATIONS

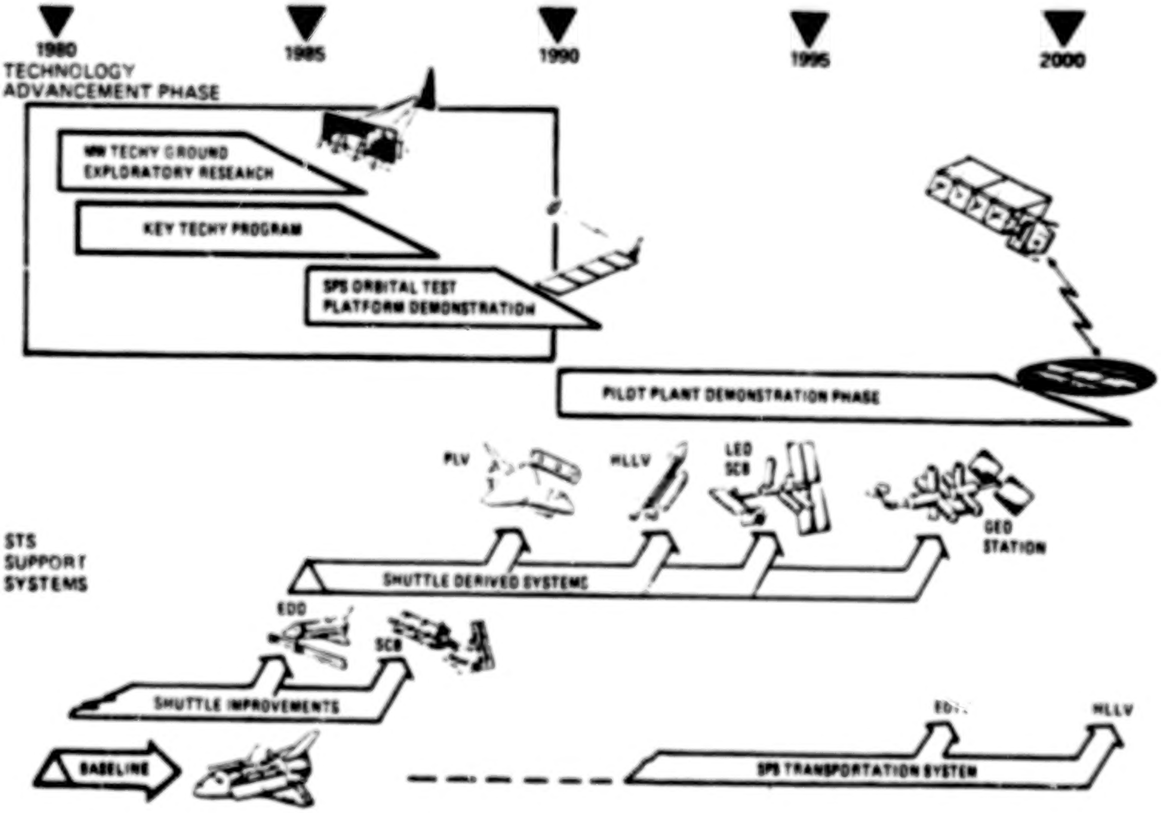
- ✓ ESTABLISH THE RELATIONSHIP OF AN EXPLORATORY RESEARCH PLAN TO THE OVERALL TECHNOLOGY ADVANCEMENT PLAN
- ✓ INTEGRATE DOE ENVIRONMENTAL STUDIES, NASA 5-YEAR PLANNING, AND SPS DEVELOPMENT PLANNING

EVALUATE AND STRUCTURE AN SPS TECHNOLOGY DEVELOPMENT PROGRAM BASED ON THESE REQUIREMENTS

- ✓ MINIMIZE FRONT-END COSTS
- ✓ UTILIZE SHUTTLE CAPABILITY TO MAXIMUM
- ✓ MAXIMIZE GROUND TESTING
- ✓ REFLECT REASONABLE LEAD TIMES

EVOLVE DEVELOPMENT PLANNING REQUIREMENTS FOR THESE KEY INITIAL DEVELOPMENT PLAN ELEMENTS

- ✓ GROUND DEVELOPMENT/ANALYSIS
- ✓ ORBITAL DEVELOPMENT/DEMONSTRATION
- ✓ MASS-TRANSFER CAPABILITY


1980
1985
1990
1995
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TECHNOLOGY ADVANCEMENT PHASE
MW TECHY GROUND EXPLORATORY RESEARCH
KEY TECHY PROGRAM
SPS ORBITAL TEST PLATFORM DEMONSTRATION
PILOT PLANT DEMONSTRATION PHASE
PLV
HLLV
LEO SCB
GEO STATION
STS SUPPORT SYSTEMS
SHUTTLE DERIVED SYSTEMS
EDO
SCB
SHUTTLE IMPROVEMENTS
BASELINE
EOTV
HLLV
SPS TRANSPORTATION SYSTEM

*Figure 1.2-1. SPS Evolutionary Development Plan Elements*

## 1.3 SPS DEVELOPMENT PLANNING SCENARIO OVERVIEW - 1978

The expanded SPS development planning scenario overview shown in Figure 1.3-1 was developed to reflect a perceived consensus relating to current development planning options. The scenario illustrates a synthesized program reflecting current recommendations and projected five-year plans for exploratory research, technology advancement, and pilot-plant demonstration. A development cycle of 20 to 25 years is projected, leading to an initial operating capability about the year 2003 for the first commercial system. The plan consists of two principal phases: a technology advancement phase (1980 to 1990) and a pilot plant demonstration phase (1990 to 2000).

Key elements within the SPS planning scenario include the DOE exploratory research program, the overall key technology program (supported by NASA enabling technology effort), the pilot plant demonstration plan, and the required support system developments in transportation and space construction.

The exploratory research plan element provides the seed-bed for prototype development of microwave power transmission systems (MPTS), and is reviewed in Section 2.3.

The key technology program for power conversion and distribution and development of large space structures is structured to provide evolutionary timelines leading to large SPS-type subscale space test articles and is discussed in detail in Section 2.4. The commitment to large-scale SPS development ground and space test activity will occur about 1985 based upon exploratory research program results and will require funding levels on the order of several billions of dollars. The orbital test program is reviewed in Section 2.5.

The pilot-plant demonstration phase reflects in general the "precursor" demonstration concept proposed as the most cost-effective approach to large-scale pilot-plant commercial end-to-end performance demonstration. Utilization of Shuttle-derived heavy-lift launch vehicles with low earth orbit (LEO) assembly and dedicated electric propulsion orbital transfer to geosynchronous orbit (GEO) is baselined. The pilot-plant phase is reviewed in Section 3.0. In this report the emphasis is primarily directed toward amplification of the technology advancement phase of the SPS development plan for the projected time frame of 1980 to 1990.

## 1.4 SPS DEVELOPMENT ACHIEVEMENT PROBABILITY

In any evolutionary development program projected substantial completion of major test phase elements is conditioned by technical progress, funding levels and the degree of institutional and public support. It is convenient under these circumstances to express projected test phase accomplishment as a probability-of-occurrence distribution as summarized in Figure 1.4-1.

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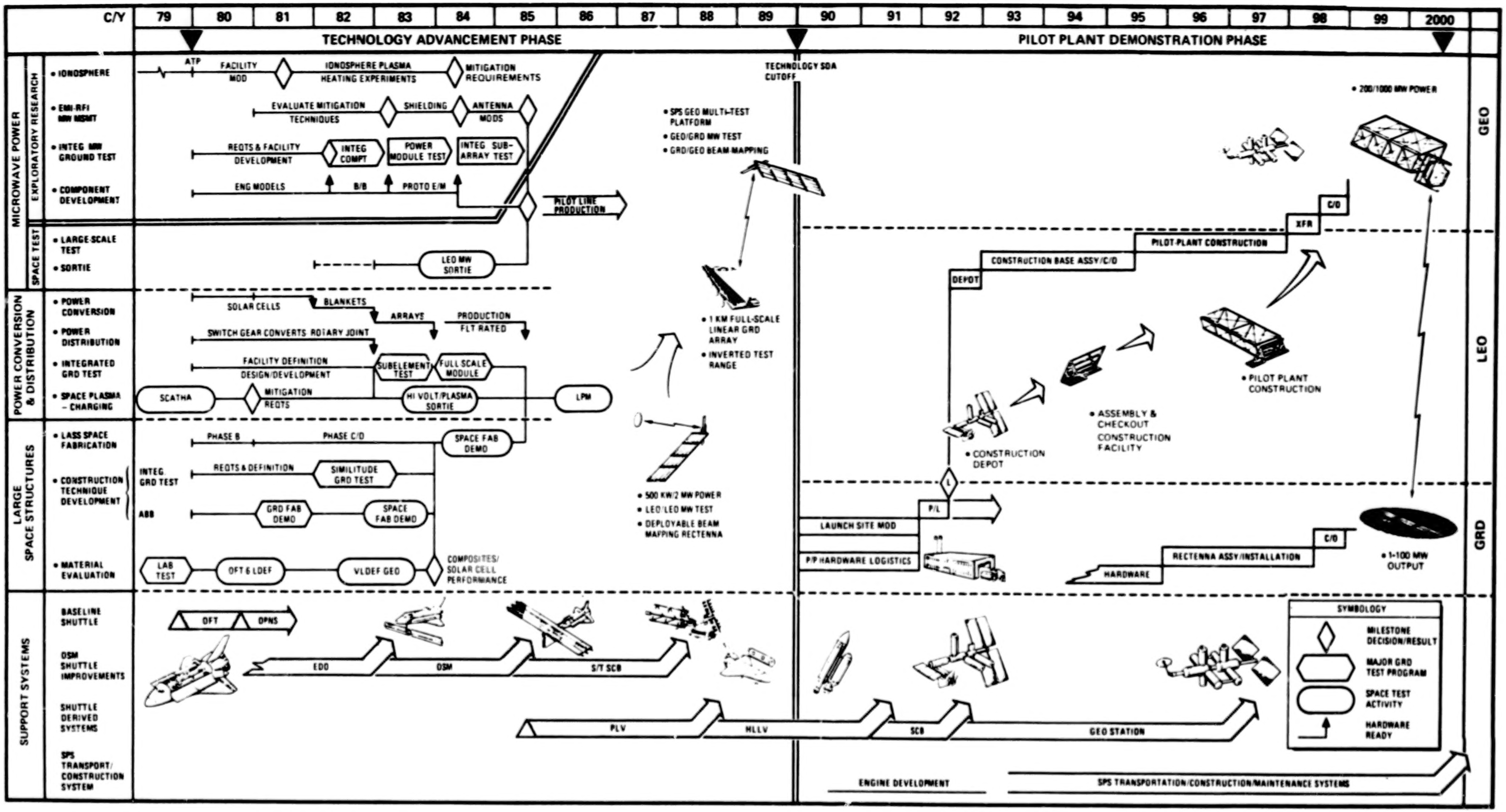
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2000
TECHNOLOGY ADVANCEMENT PHASE
PILOT PLANT DEMONSTRATION PHASE
MICROWAVE POWER
EXPLORATORY RESEARCH
• IONOSPHERE
ATP
FACILITY MOD
IONOSPHERE PLASMA HEATING EXPERIMENTS
MITIGATION REQUIREMENTS
• EMI-RFI MW MSMT
EVALUATE MITIGATION TECHNIQUES
SHIELDING
ANTENNA MODS
• INTEG MW GROUND TEST
REQTS & FACILITY DEVELOPMENT
INTEG COMPT
POWER MODULE TEST
INTEG SUB-ARRAY TEST
• COMPONENT DEVELOPMENT
ENG MODELS
B/B
PROTO E/M
PILOT LINE PRODUCTION
SPACE TEST
• LARGE-SCALE TEST
• SORTIE
LEO MW SORTIE
POWER CONVERSION & DISTRIBUTION
• POWER CONVERSION
SOLAR CELLS
BLANKETS
ARRAYS
PRODUCTION FLT RATED
• POWER DISTRIBUTION
SWITCH GEAR CONVERTS ROTARY JOINT
• INTEGRATED GRD TEST
FACILITY DEFINITION DESIGN/DEVELOPMENT
SUBELEMENT TEST
FULL SCALE MODULE
• SPACE PLASMA – CHARGING
SCATHA
MITIGATION REQTS
HI VOLT/PLASMA SORTIE
LPM
LARGE SPACE STRUCTURES
• LASS SPACE FABRICATION
PHASE B
PHASE C/D
SPACE FAB DEMO
• CONSTRUCTION TECHNIQUE DEVELOPMENT
INTEG. GRD TEST
REQTS & DEFINITION
SIMILITUDE GRD TEST
ABB
GRD FAB DEMO
SPACE FAB DEMO
• MATERIAL EVALUATION
LAB TEST
OFT 6 LDEF
VLDEF GEO
COMPOSITES/ SOLAR CELL PERFORMANCE
SUPPORT SYSTEMS
BASELINE SHUTTLE
OFT
OPNS
OSM SHUTTLE IMPROVEMENTS
EDO
OSM
S/T SCB
SHUTTLE DERIVED SYSTEMS
PLV
HLLV
SCB
GEO STATION
SPS TRANSPORT/ CONSTRUCTION SYSTEM
ENGINE DEVELOPMENT
SPS TRANSPORTATION/CONSTRUCTION/MAINTENANCE SYSTEMS
TECHNOLOGY SDA CUTOFF
• SPS GEO MULTI-TEST PLATFORM
• GEO/GRD MW TEST
• GRD/GEO BEAM MAPPING
• 1 KM FULL-SCALE LINEAR GRD ARRAY
• INVERTED TEST RANGE
• 500 KW/2 MW POWER
• LEO/LEO MW TEST
• DEPLOYABLE BEAM MAPPING RECTENNA
• 200/1000 MW POWER
GEO
LEO
GRD
C/O
XFR
PILOT-PLANT CONSTRUCTION
CONSTRUCTION BASE ASSY/C/O
DEPOT
• PILOT PLANT CONSTRUCTION
• ASSEMBLY & CHECKOUT CONSTRUCTION FACILITY
• CONSTRUCTION DEPOT
L
P/L
LAUNCH SITE MOD
P/P HARDWARE LOGISTICS
HARDWARE
RECTENNA ASSY/INSTALLATION
C/O
• 1-100 MW OUTPUT
SYMBOLOGY
MILESTONE DECISION/RESULT
MAJOR GRD TEST PROGRAM
SPACE TEST ACTIVITY
HARDWARE READY

*Figure 1.3-1. SPS Development Planning Scenario Overview - 1978*

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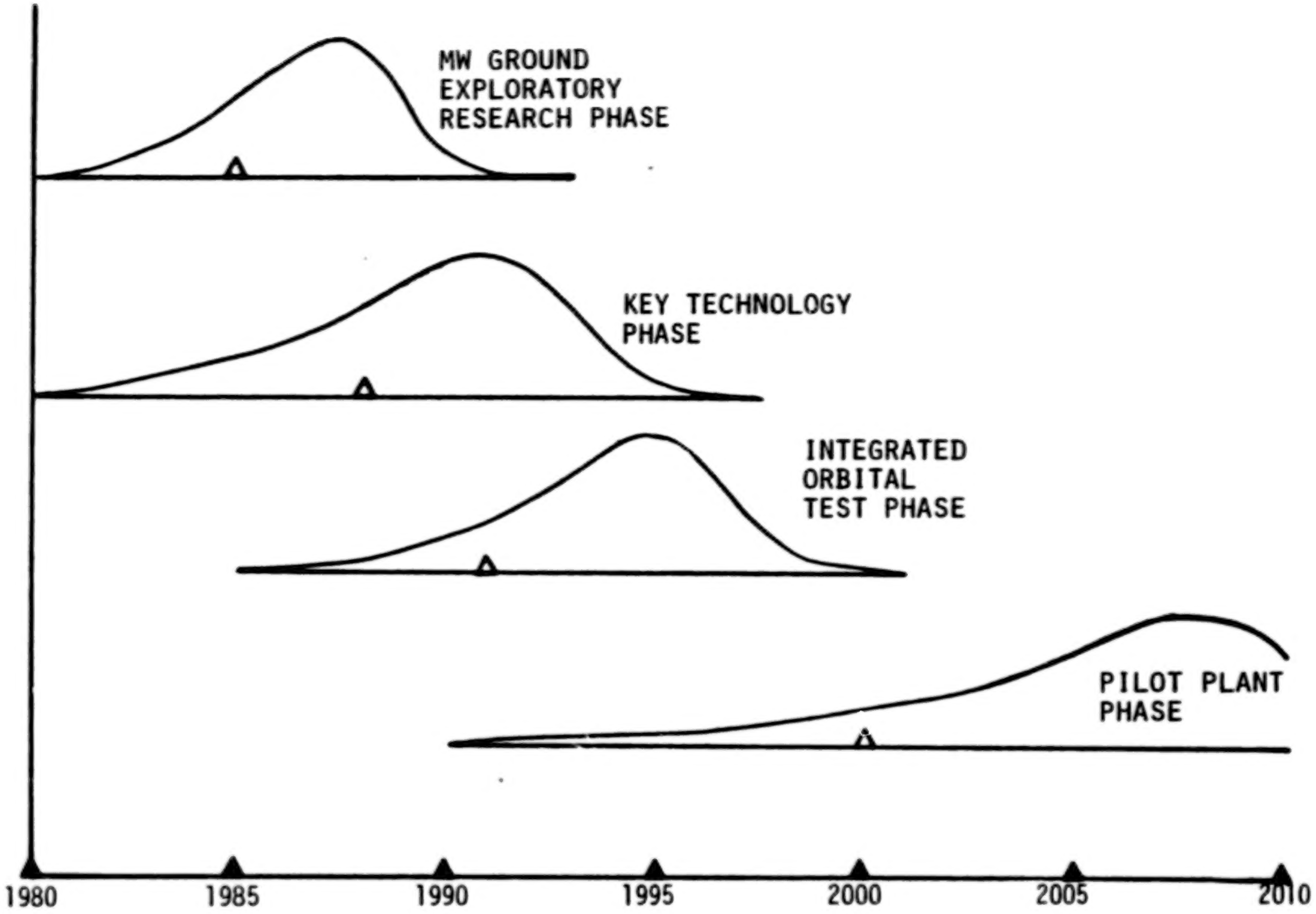


*Figure 1.4-1. SPS Test Phase Accomplishment Probability Distributions*

# 2.0 SPS TECHNOLOGY ADVANCEMENT PHASE

## 2.1 CRITICAL TECHNOLOGY ISSUES

The basic objective of the SPS Technology Advancement Phase is to evaluate and resolve the critical technology issues related to the SPS preliminary reference configuration.

The critical issues that could prevent successful development of the currently postulated SPS system can be grouped in two major categories:

- Effects of the SPS system on the environment
  - ✓ Interactions of the microwave beam with the ionosphere
  - ✓ Effects of launch vehicle emissions on the upper atmosphere
  - ✓ Microwave system radio frequency interference with other systems
  - ✓ Microwave radiation effects on primates and ecology
- Effects of the natural environment on SPS system development and operation
  - ✓ Radiation effects on space construction and operations personnel
  - ✓ Space plasma effects on high-voltage power conversion and power amplification
  - ✓ Space environment effects on materials life-time, strength and efficiency

Each of these critical environmental interaction issues requires concentrated experimental research to quantify the probable effects and provide a programmatic technical basis for deriving mitigation techniques. The impact of these "driving" technical issues upon SPS system and subsystem concept definition and operational sequences is matrixed in Table 2.1-1.

SPS critical technical issue experimental results will impact in varying degrees, all of the subsystems and system support elements shown in the table.

### 2.1.1 MICROWAVE POWER

The microwave power transmission system (MPTS) is clearly the most critical subsystem from the standpoint of environmental impact vulnerability and basic technical feasibility. State-of-the-art advances are required in dc/RF and RF/dc conversion, phase control, RFI suppression and thermal control. Undesirable effects upon the environment and environmentally induced degradation of key microwave power components and elements will result in an iterative subsystem definition cycle involving significant trade study of potential options and alternative designs.

*Table 2.1-1. Technology Issue Impact on Key Subsystems*

| CRITICAL TECHNICAL ISSUES | SYSTEMS DEVELOPMENT/OPERATIONS IMPACT | | | |
|---|---|---|---|---|
| ● EFFECTS OF SPS ON ENVIRONMENT | MICROWAVE POWER | POWER CONVERSION AND DISTRIBUTION | STRUCTURE AND CONSTRUCTION | MASS TRANSFER |
| ✓ INTERACTION OF MICROWAVE BEAM WITH IONOSPHERE | ✓ | | | |
| ✓ EFFECT OF LAUNCH VEHICLE EMISSIONS | | | | ✓ |
| ✓ MICROWAVE SYSTEM RFI EFFECTS | ✓ | | | |
| ✓ MICROWAVE EFFECTS ON PRIMATES/ECOLOGY | ✓ | | | |
| ● EFFECTS OF ENVIRONMENT ON SPS | | | | |
| ✓ SPACE RADIATION EFFECTS ON PERSONNEL | | | ✓ | ✓ |
| ✓ SPACE PLASMA EFFECTS | ✓ | ✓ | | |
| ✓ SPACE ENVIRONMENTAL EFFECTS ON MATERIALS | ✓ | ✓ | ✓ | |

Undesirable effects of incident energy and spurious emissions upon performance of civil and military equipment operating in affected microwave regimes as well as potential modification of the ionosphere that could substantially alter the propagation of radio signals over a wide range of frequencies, may require mandatory changes and option trades for the following reference system characteristics and equipment elements:

- ✓ Transmission Frequency
- ✓ Power Beam Maximum Density and Taper
- ✓ Power Amplifier Selection (Klystron vs Solid State)
- ✓ Phase Front Control Circuitry
- ✓ Rectenna Size and RF/dc Converter Selection

### 2.1.2 POWER CONVERSION AND DISTRIBUTION

Space plasma effects upon the materials properties of solar cells, solar array interconnects, reflector films, conductor/insulations and overall high-voltage power system performance will require decisions relative to the following option issues:

- ✓ Solar cell selection - (GaAs vs Silicon)
- ✓ Solar cell annealing technique
- ✓ Concentration ratio
- ✓ Reflector materials
- ✓ Power distribution voltage level

### 2.1.3 STRUCTURE AND CONSTRUCTION

UV/particle radiation effects on composite materials baselined for SPS structure are unknown and possible outgasring characteristics remain to be resolved. In addition, composites are relatively poor electrical conductors, and wherever composite structure interfaces with metallic parts, local discharges could produce structural damage to the composite material.

The capability of man to function efficiently for an extended duration in geosynchronous orbit is a key issue in basic SPS construction scenarios, and overall system cost-effectiveness considerations. The effects of H-E particles on space worker stay times may have a significant impact on construction methodology and location.

The following option issues are visualized:

- ✓ Structural materials selection (aluminum vs composites)
- ✓ Space construction location (LEO vs GEO vs Hybrid)

### 2.1.4 LAUNCH VEHICLE/OTV MASS TRANSFER

The demonstrated effect of F layer depletion due to large hydrogen or hydrocarbon-burning rocket emissions poses a serious constraint upon SPS development feasibility and impacts the following trade options:

- ✓ Launch trajectory selection and rate
- ✓ Propulsion system selection

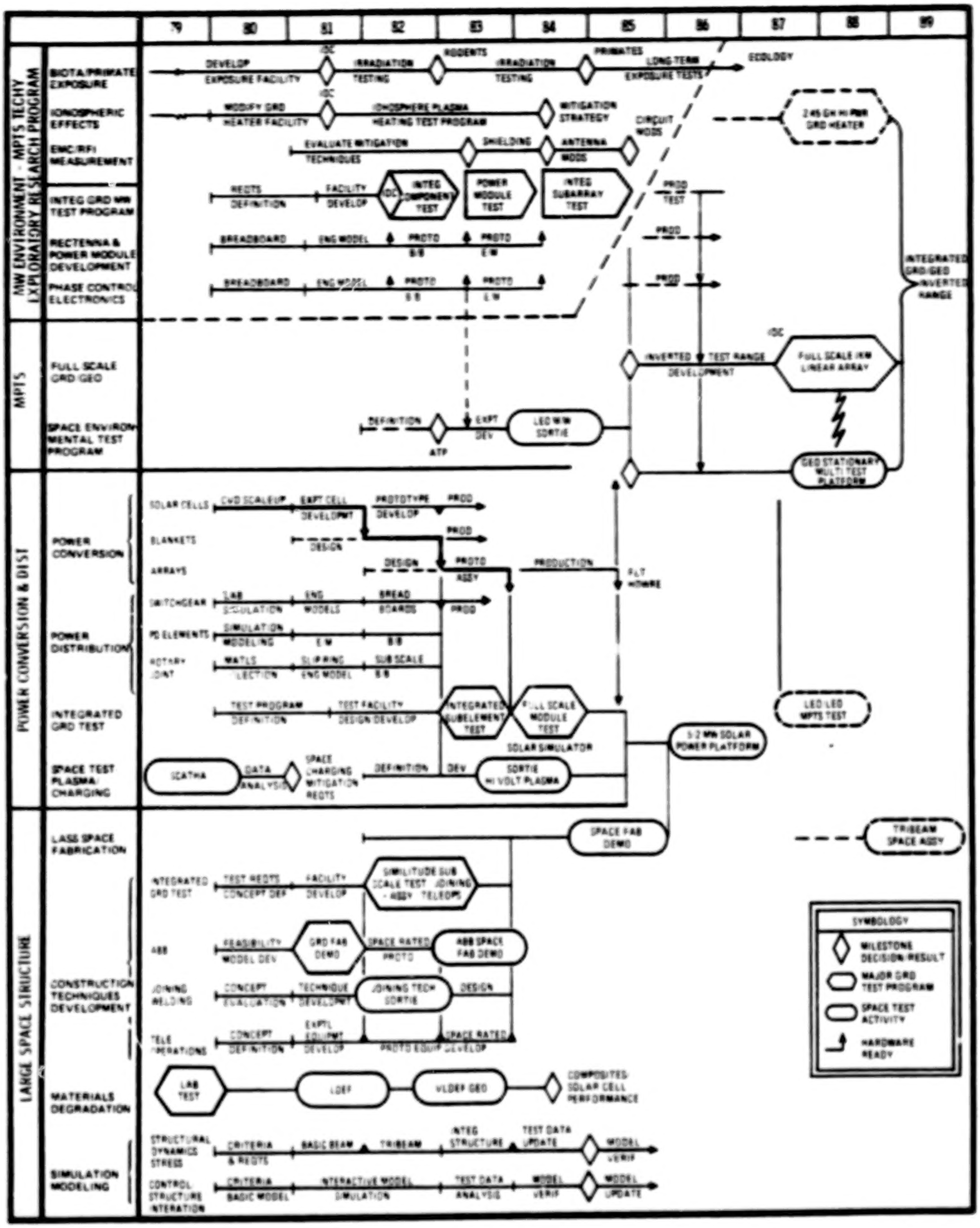
## 2.2 TECHNOLOGY ADVANCEMENT PLANNING NETWORK

A second-level synthesis of the "front end" technology advancement plan is shown in Figure 2.2-1. The proposed DOE exploratory research program is contained within the dashed line, and represents the principal microwave technology development effort during the period 1980 to 1985.

The overall technology plan reflects a strong emphasis on early comprehensive ground-testing supported as necessary by Shuttle sortie experiments, and leads to technology readiness by 1990. Power conversion and distribution and large structure technology development time-lines reflect current NASA focused plans through 1985. SPS development progress will be a function of the funding support ultimately provided against the planning requirements. The three principal elements constituting the SPS technology advancement plan include DOE microwave exploratory research, other subsystem key technology, and the ultimate large orbital test vehicle program (that will evolve from the subsystem ground and sortie developmental effort) during the period from 1985 through 1990. Each of these major test plan elements will be expanded upon in this section.

The orbital test elements of the SPS technology advancement program will be supported by the Shuttle transportation system and its improvements and derivatives. Large SPS subscale orbital test articles will require an extended-duration orbiter and a Shuttle-tended LEO construction base. Subsequent pilot-plant construction after 1990 will involve very large mass transfer requirements to LEO as well as self-sustaining manned construction facilities in LEO which require the development of a Shuttle-derived low-cost (<$100/lb to LEO) heavy-lift launch vehicle. This development should start about 1985 to support the planned scenario.

As indicated earlier, SPS microwave power transmission technology is the critical technology determinant in early SPS key issue evaluation. The technology uncertainties involved will be explored in the proposed DOE microwave research program.



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MW ENVIRONMENT - MPTS TECHY EXPLORATORY RESEARCH PROGRAM
BIOTA/PRIMATE EXPOSURE
DEVELOP EXPOSURE FACILITY
IOC
IRRADIATION TESTING
RODENTS
IRRADIATION TESTING
PRIMATES
LONG TERM EXPOSURE TESTS
ECOLOGY
IONOSPHERIC EFFECTS
MODIFY GRD HEATER FACILITY
IOC
IONOSPHERE PLASMA HEATING TEST PROGRAM
MITIGATION STRATEGY
CIRCUIT MODS
EMC/RFI MEASUREMENT
EVALUATE MITIGATION TECHNIQUES
SHIELDING
ANTENNA MODS
INTEG GRD MW TEST PROGRAM
REQTS DEFINITION
FACILITY DEVELOP
IOC
INTEG COMPONENT TEST
POWER MODULE TEST
INTEG SUBARRAY TEST
PROD TEST
RECTENNA & POWER MODULE DEVELOPMENT
BREADBOARD
ENG MODEL
PROTO B/B
PROTO E/M
PROD
PHASE CONTROL ELECTRONICS
BREADBOARD
ENG MODEL
PROTO B/B
PROTO E/M
PROD
2.45 GH HI PWR GRD HEATER
INTEGRATED GRD/GEO INVERTED RANGE
MPTS
FULL SCALE GRD/GEO
INVERTED TEST RANGE DEVELOPMENT
IOC
FULL SCALE I KM LINEAR ARRAY
SPACE ENVIRONMENTAL TEST PROGRAM
DEFINITION
ATP
EXPT DEV
LEO MW SORTIE
GEO STATIONARY MULTI TEST PLATFORM
POWER CONVERSION & DIST
POWER CONVERSION
SOLAR CELLS
CVD SCALEUP
EXPT CELL DEVELOPMT
PROTOTYPE DEVELOP
PROD
BLANKETS
DESIGN
PROD
ARRAYS
DESIGN
PROTO ASSY
PRODUCTION
FLT HDWRE
POWER DISTRIBUTION
SWITCHGEAR
LAB SIMULATION
ENG MODELS
BREAD BOARDS
PROD
PD ELEMENTS
SIMULATION MODELING
E/M
B/B
ROTARY JOINT
MATLS SELECTION
SLIP RING ENG MODEL
SUB SCALE B/B
INTEGRATED GRD TEST
TEST PROGRAM DEFINITION
TEST FACILITY DESIGN/DEVELOP
INTEGRATED SUBELEMENT TEST
FULL SCALE MODULE TEST
SOLAR SIMULATOR
LEO/LEO MPTS TEST
SPACE TEST PLASMA/CHARGING
SCATHA
DATA ANALYSIS
SPACE CHARGING MITIGATION REQTS
DEFINITION
DEV
SORTIE HI VOLT PLASMA
1-2 MW SOLAR POWER PLATFORM
LARGE SPACE STRUCTURE
LASS SPACE FABRICATION
SPACE FAB DEMO
TRIBEAM SPACE ASSY
CONSTRUCTION TECHNIQUES DEVELOPMENT
INTEGRATED GRD TEST
TEST REQTS CONCEPT DEF
FACILITY DEVELOP
SIMILITUDE SUB SCALE TEST JOINING - ASSY TELEOPS
ABB
FEASIBILITY MODEL DEV
GRD FAB DEMO
SPACE RATED PROTO
ABB SPACE FAB DEMO
JOINING WELDING
CONCEPT EVALUATION
TECHNIQUE DEVELOPMT
JOINING TECH SORTIE
DESIGN
TELE OPERATIONS
CONCEPT DEFINITION
EXPTL EQUIPMT DEVELOP
SPACE RATED PROTO EQUIP DEVELOP
MATERIALS DEGRADATION
LAB TEST
LDEF
VLDEF GEO
COMPOSITES SOLAR CELL PERFORMANCE
SIMULATION MODELING
STRUCTURAL DYNAMICS STRESS
CRITERIA & REQTS
BASIC BEAM
TRIBEAM
INTEG STRUCTURE
TEST DATA UPDATE
MODEL VERIF
CONTROL STRUCTURE INTERATION
CRITERIA BASIC MODEL
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TEST DATA ANALYSIS
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MODEL UPDATE
SYMBOLOGY
MILESTONE DECISION/RESULT
MAJOR GRD TEST PROGRAM
SPACE TEST ACTIVITY
HARDWARE READY

*Figure 2.2-1. SPS Technology Advancement Planning Network*

## 2.3 DOE GROUND EXPLORATORY RESEARCH PROGRAM

The objective of the current joint SPS concept evaluation program is to develop by the end of 1980 an initial understanding of the economic practicality and the social and environmental acceptability of the SPS concept. At the present time, the degree of uncertainty of all aspects of SPS is high, particularly with respect to environmental impact.

In 1980, the DOE with NASA technical support, plans to initiate a comprehensive ground-based exploratory research effort that is SPS oriented, environmentally driven, and aimed at reducing the uncertainty associated with the critical environmental/technical issues. Initial planned FY 1980 funding will be on the order of $8 M.

### 2.3.1 OVERALL EXPLORATORY RESEARCH PROGRAM ELEMENTS

Major elements of the exploratory research plan include:

- Microwave Effects
    - Health and Safety
    - Ecology
    - Communications
    - Technology
- Research Integration and Management Planning

Research for microwave effects on health and safety of humans, animals and the ecology will focus on deriving experimental evidence relative to low dose, long term exposure effects, high dose, short term exposure effects and verification of SPS microwave technology.

Planned effort in the area of microwave effects on communications will focus on measurements of effects on communications, navigation and command and control systems. The test program will orient to RFI, EMC and E/M harmonics and will include experimentation on effects of microwave transmission upon the ionosphere. SPS microwave technology will be verified through measurements of efficiency of mitigation strategies. The test logic sequence is shown in Figure 2.3-1.

The key test element in the overall exploratory research program will be the NASA supported microwave technology phase which will evaluate the technical viability of SPS power transmission by microwave beam. This effort will generate and evaluate test hardware for microwave generation, beam formation and control and noise/harmonics suppression.

### 2.3.2 GROUND-BASED EXPLORATORY RESEARCH - MICROWAVE TECHNOLOGY

The objective of the program is to conduct technology research in critical areas associated with the SPS microwave system, develop near-prototypical hardware, integrate this hardware in an optimum subarray design, conduct integrated tests, and produce performance data for use in the environmental analysis program. A secondary objective is a continuing technology program in the critical areas (klystron, phase control, solid state) that will provide

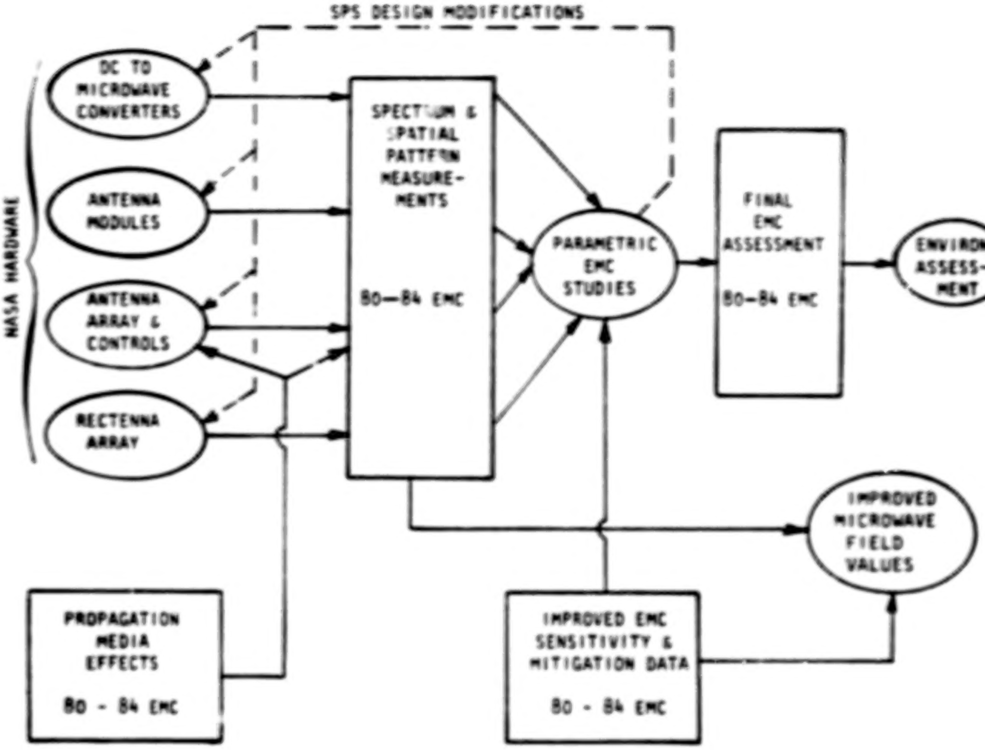

SPS DESIGN MODIFICATIONS
NASA HARDWARE
DC TO MICROWAVE CONVERTERS
ANTENNA MODULES
ANTENNA ARRAY & CONTROLS
RECTENNA ARRAY
SPECTRUM & SPATIAL PATTERN MEASUREMENTS
80—84 EMC
PARAMETRIC EMC STUDIES
FINAL EMC ASSESSMENT
80—84 EMC
ENVIRON. ASSESSMENT
IMPROVED MICROWAVE FIELD VALUES
PROPAGATION MEDIA EFFECTS
80 - 84 EMC
IMPROVED EMC SENSITIVITY & MITIGATION DATA
80 - 84 EMC

*Figure 2.3-1. Microwave Effects Test Logic Sequence*

progressive development to support the technology advancement program. Development and integrated testing of near-prototypical hardware will provide a much stronger data base for economic assessments of the SPS program.

The major elements of the microwave technology (GBER) plan and their interrelationship are shown in Figure 2.3-2. As a background note the first early microwave power transfer work was accomplished at MSFC in 1969. This was a low power laboratory test and demonstrated concept only. The first significant large RF power transfer was accomplished by JPL in 1975. This test used a large dish antenna and a single power tube. It was a significant demonstration of power transfer but did not simulate the performance of the microwave system as proposed by current SPS system studies. There have been no environmental analyses performed on the microwave system that have been based on actual performance data. This plan will provide a vehicle for producing prototypical performance data through a significant microwave component technology development program. These data can then be used as the data base for the environmental assessment of the microwave system. Uncertainties associated with the predictions of microwave system performance will then be greatly reduced.

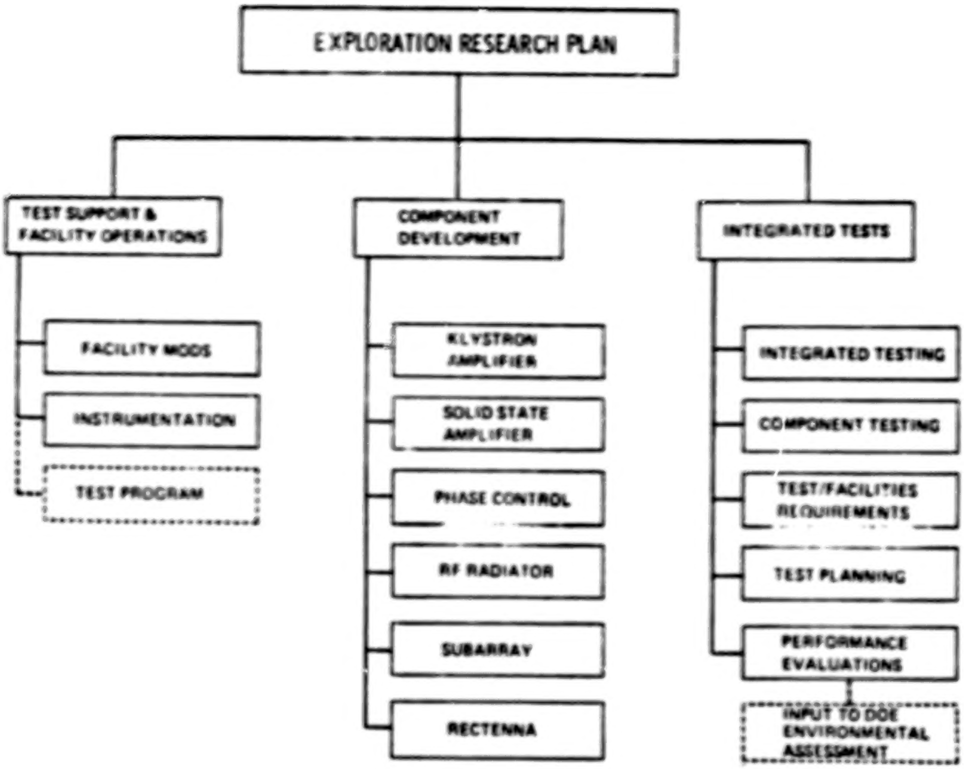

EXPLORATION RESEARCH PLAN
TEST SUPPORT & FACILITY OPERATIONS
FACILITY MODS
INSTRUMENTATION
TEST PROGRAM
COMPONENT DEVELOPMENT
KLYSTRON AMPLIFIER
SOLID STATE AMPLIFIER
PHASE CONTROL
RF RADIATOR
SUBARRAY
RECTENNA
INTEGRATED TESTS
INTEGRATED TESTING
COMPONENT TESTING
TEST/FACILITIES REQUIREMENTS
TEST PLANNING
PERFORMANCE EVALUATIONS
INPUT TO DOE ENVIRONMENTAL ASSESSMENT

*Figure 2.3-2. Major Elements of Ground Based Exploratory Research (GBER) Program*

The microwave technology exploratory research plan has been structured within the following guidelines.

- Provide the instrumentation and data gathering hardware necessary to support the integrated tests and provide sufficient data for input to the economic and environmental assessments of the SPS program. Anechoic chambers and ranges will be needed to provide the quiet zones and far field analysis to adequately test the performance of the hardware. EMI and RFI characteristics such as harmonics and noise require low level, high accuracy measurements within a shielded anechoic chamber. Accurate beam mapping and gain measurements will require an RF antenna range of sufficient length to encompass far field patterns.
- Develop near prototypical hardware in critical areas.
- Develop data base for economic and environmental assessments.
- Establish sufficient program continuation milestones for progressive program development.
- Provide qualitative data for microwave feasibility and performance evaluation.

The general flow of the GBER is illustrated in Figure 2.3-3. This chart describes a progressive product oriented development and test program with key milestones.

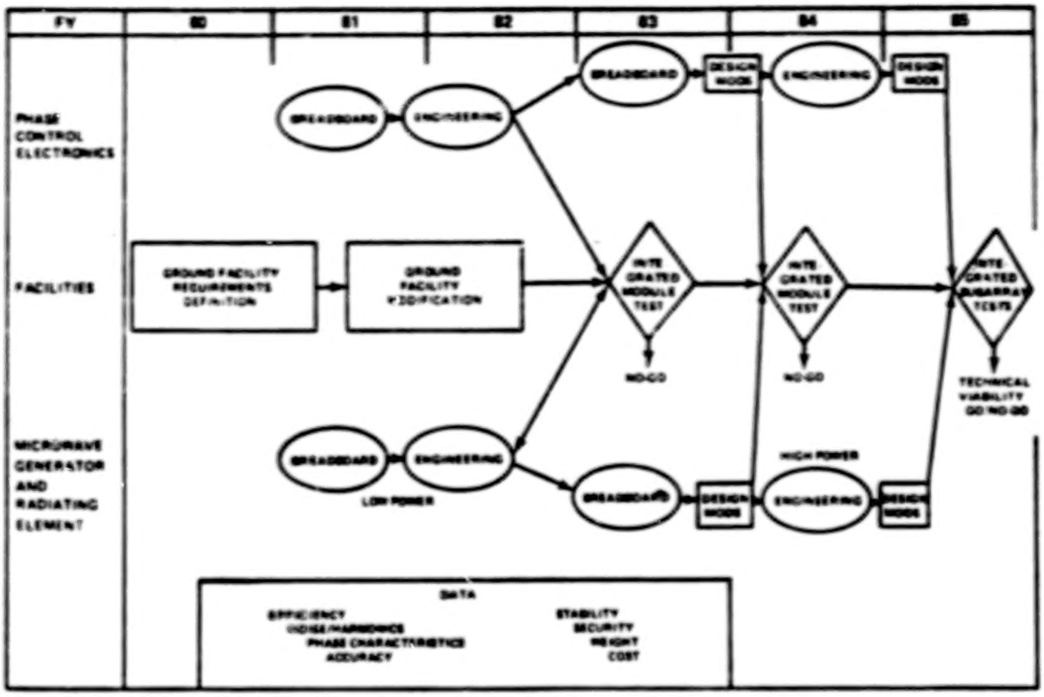

FY
80
81
82
83
84
85
PHASE CONTROL ELECTRONICS
FACILITIES
MICROWAVE GENERATOR AND RADIATING ELEMENT
BREADBOARD
ENGINEERING
BREADBOARD
DESIGN MODS
ENGINEERING
DESIGN MODS
GROUND FACILITY REQUIREMENTS DEFINITION
GROUND FACILITY MODIFICATION
INTEGRATED MODULE TEST
NO-GO
INTEGRATED MODULE TEST
NO-GO
INTEGRATED SUBARRAY TESTS
TECHNICAL VIABILITY GO/NO-GO
BREADBOARD
ENGINEERING
LOW POWER
BREADBOARD
DESIGN MODS
HIGH POWER
ENGINEERING
DESIGN MODS
DATA
EFFICIENCY
NOISE/HARMONICS
PHASE CHARACTERISTICS
ACCURACY
STABILITY
SECURITY
WEIGHT
COST

*Figure 2.3-3. Technical Approach (Schedule/Results)*

The microwave technology GBER plan is divided into three major parts: test support and facility operations, integrated tests, and component development. Component development is further subdivided into klystron amplifier, solid state amplifier, phase control, RF radiator, subarray, and rectenna. Each part contributes to the ultimate objective of determining the performance characteristics of a near prototypical SPS subarray. An example of the type facility required to support this development and testing is illustrated in Figure 2.3-4. This facility can provide for testing, data collecting, and data analysis. Some typical performance monitored parameters are RMS phase error, reflected RF power, and sidelobe levels.

The integrated test element will provide design requirements for the facility and instrumentation. Integrated testing is subdivided into power module tests, test article tests, and subarray tests. This method provides a step-by-step buildup for an ultimate SPS subarray test and allows key decision points along the way.

The third part of the GBER is component development. It is perhaps the most important part because most of the technology development occurs here. It is the technological progress with key component developments that will ultimately determine the performance characteristics of the near prototypical

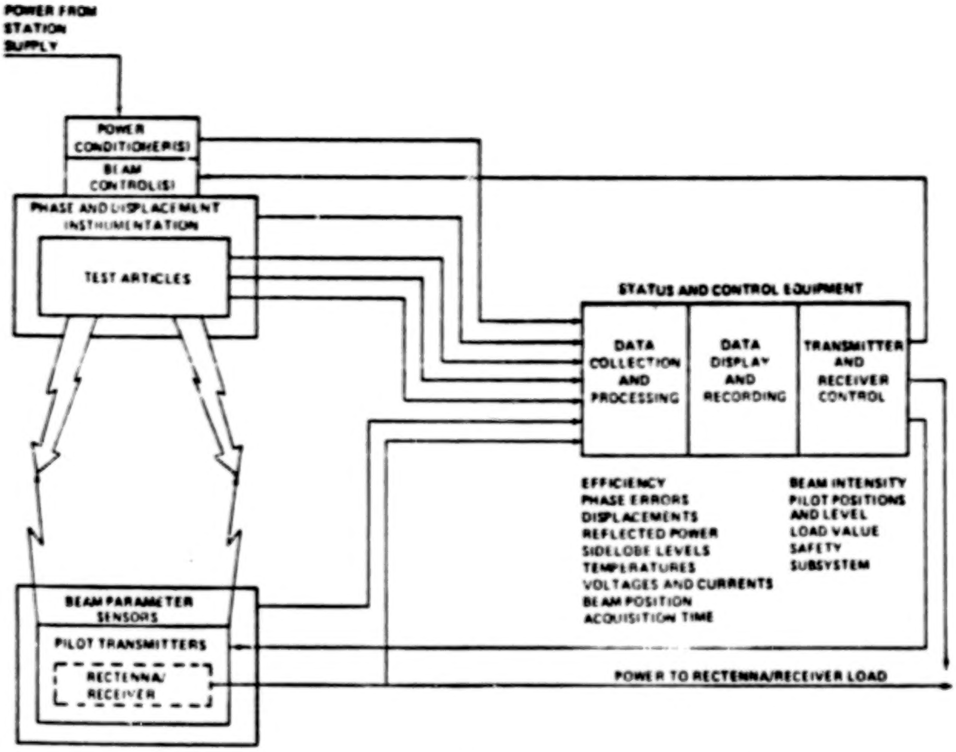

POWER FROM STATION SUPPLY
POWER CONDITIONER(S)
BEAM CONTROL(S)
PHASE AND DISPLACEMENT INSTRUMENTATION
TEST ARTICLES
STATUS AND CONTROL EQUIPMENT
DATA COLLECTION AND PROCESSING
DATA DISPLAY AND RECORDING
TRANSMITTER AND RECEIVER CONTROL
EFFICIENCY
PHASE ERRORS
DISPLACEMENTS
REFLECTED POWER
SIDELOBE LEVELS
TEMPERATURES
VOLTAGES AND CURRENTS
BEAM POSITION
ACQUISITION TIME
BEAM INTENSITY
PILOT POSITIONS AND LEVEL
LOAD VALUE
SAFETY
SUBSYSTEM
BEAM PARAMETER SENSORS
PILOT TRANSMITTERS
RECTENNA/ RECEIVER
POWER TO RECTENNA/RECEIVER LOAD

*Figure 2.3-4. Functional Block Diagram of Test Facility*

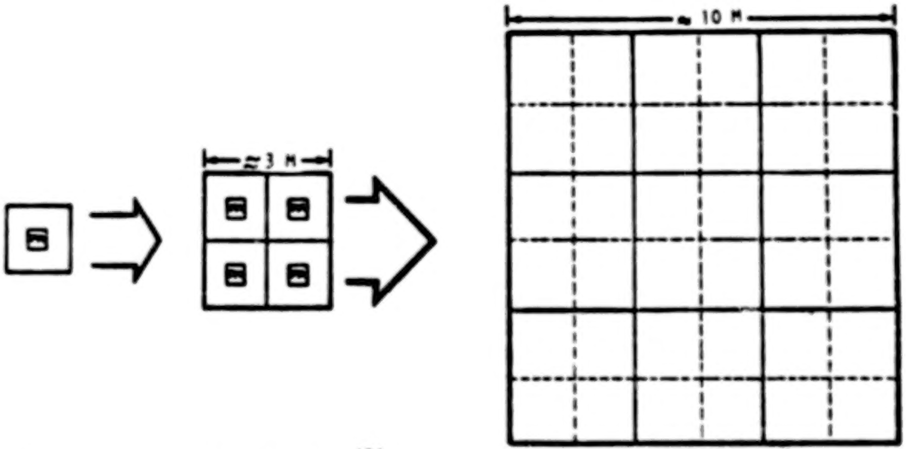
SPS subarray. Several key elements of the microwave system have been selected for technology investigations.

Integrated Test Plan

The major objectives of this project are the effective management and technical integration of the various microwave system elements. Each system element must support its own objectives and the system objective of integration and performance testing of a near prototypical SPS subarray. Specifically this would be performance verification of critical microwave system parameters that include transmission efficiency, beam forming accuracy, beam steering accuracy, power beam/pilot signal isolation, mechanical alignment/tolerances, RF/dc conversion efficiencies, and analysis of the interaction of subsystems and elements. The feasibility of a microwave system to transmit power at the high efficiencies required for SPS when the combined effects of system hardware imperfections are considered must be experimentally verified. The performance of the SPS system is critically dependent on the phase distribution/control electronics, power amplifier, and radiating elements when operating in a large subarray system configuration. Tests of such a system have not been accomplished with accuracies sufficient to establish performance capabilities required to meet the SPS specifications.

Progressive testing from component development to power module and finally to subarray level testing will provide performance data for assessing the feasibility of the SPS microwave system. Key milestones focus the testing to allow effective management decisions and provide data at the end of performance evaluation and inputs to the DOE environmental analysis program.

Early integrated test planning is essential for facility development and instrumentation definition with the first two years (1980-1981) devoted to planning and requirements definition at a low level of funding. Some software and procedure definition will occur in 1981 with actual development of the software and procedures for testing to be completed in 1982. The facilities will then be ready for checkout and verification of software and procedures to support the power module tests in 1983. Integrated tests have three major hardware components for testing (Figure 2.3-5), namely the power module, test article, and subarray. The test program is described in the following paragraphs.



POWER MODULE

POWER AMPLIFIER
FEED SYSTEMS
PHASE LOCK LOOP
FILTERS
RF RADIATOR

TEST ARTICLE[(1)]

4 POWER MODULES
1 TO 4 PHASE CONTROL SYSTEM

SUBARRAY

9 TEST ARTICLES
(36 PWR MODULES
9—36 PHASE CONTROL SYSTEMS)

(1) THIS DESIGN IS OPTIONAL, BUT IT MOST NEARLY REPRESENTS THE JOINT REFERENCE CONFIGURATION.

*Figure 2.3-5. Integrated Test Major Hardware Components*

Power Module Test. There will be at least two power module tests. One test using a klystron power amplifier and one using a solid state power amplifier. These tests will require different setups because of the uniqueness of their parameters. An example is the power requirements; the klystron would require several voltage levels in the kilovolt range and the solid state amplifier would require one very low voltage (30 to 50 V). Each power module would have its own unique components such as: RF radiator, possibly some difference in phase control, filter, power supply, and thermal control. The power module test will represent the first significant integrated test data in the microwave project and is expected to provide considerable design information for update of the component and subarray design. Testing will be required on each component or subsystem as it arrives at the test facility. This test represents the first level of integration and should produce performance information on noise and stability due to mutual coupling of components.

Test Article Tests. Two test article tests will be conducted in 1984, one klystron test and one solid-state amplifier test. This plan provides for four power modules and one phase control subsystem to make one test article. A total of ten power modules and two phase control subsystems will have to be delivered, assembled, and each component checked out before the test article tests can be conducted. The power modules tested in 1983 will be of a development nature and will not be used in the test article tests in 1984. However, one set of five power modules (four plus a spare) from the test article tests in 1984 will be used in the subarray test in 1985. Integration of the phase control conjugating electronics will be accomplished in this test. The basic ability to demonstrate retrodirectivity and the influence of mutual coupling from multiple components will be determined.

Subarray Test. A total of nine test articles will be required for the subarray test in 1985. The quantity buy for the test in 1985 will be based on 42 power modules and 10 phase control subsystems. This module will represent a near prototypical SPS subarray and will provide similar performance characteristics. The reference phase distribution system will be integrated and end to end performance will be demonstrated with multiple phase control systems.

## Component Development

Klystron Amplifier. A low power klystron will be designed with adequate characteristics to support the integrated testing and feasibility determination of an SPS subarray. Concurrently a high power tube with high efficiency, low specific weight, and a heat-pipe thermal system will be developed. Development of the low power tube is a key element in the performance of the near prototypical SPS subarray.

This development project should produce a low power klystron with a depressed collector design that demonstrates similar characteristics (phase shift, noise, and harmonic generation) to a large high power tube. Some compromises are expected because the development cycle on the low power tube will be stopped in 1983. However, it is expected that the tube will perform adequately to support the integrated tests and provide the necessary integrated performance data and input to DOE studies. The development of the high power tube should demonstrate high efficiency (goal of 85 percent), high gain (goal of 50 dB), low noise, and high reliability. A parallel development of the thermal radiator for the large klystron will be required to demonstrate an integrated power amplifier/thermal radiator design for thermal vacuum testing in 1985.

Solid State Amplifier. A solid state amplifier will be developed to support the progressive testing and demonstration of a near prototypical SPS subarray design. System studies have indicated that a power amplifier of the 1 kW range will be needed to support these tests. A phased design is planned so a decision point on power amplifier selection can be made in 1984. System studies have indicated solid state to be a viable candidate for the SPS power amplifier. There is no amplifier of this nature available currently. Technology development is needed to demonstrate the capabilities of the solid state amplifier.

This development project should produce a solid state amplifier that can be used to verify the performance of an SPS-like subarray. Specific requirements will be to demonstrate high efficiency (goal of 85 percent), establish thermal operating characteristics, low noise, increased gain, and establish a base for cost estimation. This development information will be fed back to the system studies for impact analysis on system design. An optimum power module design based on thermal data, power distribution requirements, reliability and phase control tradeoffs will result from the technology program.

RF Radiator. New RF radiator designs will be investigated as suggested in the systems studies and hardware provided to support the integration and testing of the SPS-like subarray. Specific objectives will include determination of the efficiency levels achievable for a single frequency radiator, mechanical alignments and tolerances considering efficiency and mass production, and diplexer capabilities to suppress harmonics and noise sidebands. Requirements for an SPS RF radiator differ from state of the art in two aspects, mass production and degree of reduction in tolerances required. State of the art designs are interested in tenths of a dB, and SPS is interested in tenths of a percent. Half an order of magnitude improvement in mass manufacturing and design are required.

The SPS system studies have indicated that new designs in RF radiators could offer some advantages in efficiency, weight, and mass production techniques. There are three designs that will be studied: two that relate primarily to the klystron (composite waveguide and resonant cavity radiator) and a third that relates to the solid state design. It is anticipated that there will be a number of different radiator designs pursued with the solid state power amplifier. Requirement definition and design can be delayed until 1981 to get an input from the amplifier projects. The composite waveguide and RCR will concentrate early development work in 1982 with a decision in early 1983. The selected design will support the klystron power module test in 1983.

Phase Control. This activity is designed to provide a determination of feasibility and performance evaluation of the phase control system. This project will determine phase distribution error buildup, conjugation accuracy, pilot/power beam isolation, failure effects on beam shape, power amplifier phase noise effects: identify hardware limitations; and establish system performance criteria.

Current studies indicate extremely accurate phase distribution and beam pointing will be required for SPS. Analytical efforts must be complemented with an aggressive hardware development and evaluation program to satisfactorily demonstrate the performance of the system and provide an adequate data input to the DOE environmental analysis program.

The phase control system requirements and design will be defined in the first year (1980). There are two key technology areas and one supportive area that need developing in 1981. The reference distribution subsystem will be designed and a breadboard model developed and tested in 1981. A recovery and conjugating electronics subsystem will be designed and a breadboard model developed and tested in 1981. The supporting design of a pilot transmitter will be started in 1981. This transmitter is not considered a technology item but is required for the ultimate performance of the system. Integration of the reference distribution subsystems and the recovery/conjugating electronics will occur early in 1982. A prototype design of this integrated system and the pilot transmitter will be developed and tested in 1982. These two subsystems will then be integrated into a total phase control system prototype early in 1983. No hardware is required to support the integrated test project until the test article tests in 1984. Design information will be fed to the subarray development project in 1983.

Subarray. The subarray subsystem will provide the integrated design of power modules and test articles leading to the development of a near prototypical SPS subarray in 1985. It will determine the unique characteristics of the integrated design and perform tradeoffs on cost and complexity of the subarray design.

The single most critical element in the SPS microwave system is the subarray. The subarray will determine the ultimate performance characteristics of the phased array antenna. It is necessary to develop and test a near prototypical subarray to accurately assess the performance of the SPS microwave system. This subarray should be similar in size and parts count to the expected SPS design.

This project will take the component design data, set requirements for the power module integrated design, and provide that integration. It will feed back data into the component designs and set requirements for the subarray design and integration. It will provide the integration for the test article and subarray configurations. The end result will be test data on a near prototypical SPS subarray.

Rectenna. The objective of the rectenna project is to assess feasibility of producing rectenna elements which have a sufficiently wide dynamic range to accommodate incoming power beam variations and output dc load variations. Although high efficiency (85 percent) has been demonstrated on rectenna element RF-dc conversion, these elements do not exhibit a high dynamic range. There is much to be done in determining if these elements can interface efficiently with the variations in RF power density levels and dc load before a viable rectenna concept can be demonstrated. There is also a need to demonstrate low cost manufacturing techniques for the rectenna.

The rectenna project is expected to develop a high efficient (goal of 90 percent), low cost rectenna element of sufficient size to verify performance requirements. The project should determine efficiency levels achievable and develop detailed understandings of each component, element, and subarray for predicting cost. Performance data should provide capability to predict performance of full scale SPS rectenna. This project will determine protection requirements for failure modes and develop techniques for predicting off-normal performance including harmonic scattering effects.

### 2.3.3 SUMMARY COST AND SCHEDULE

The microwave project is estimated to require funding of approximately 32 million dollars in the 1980-1985 timeframe. Figure 2.3-6 displays the

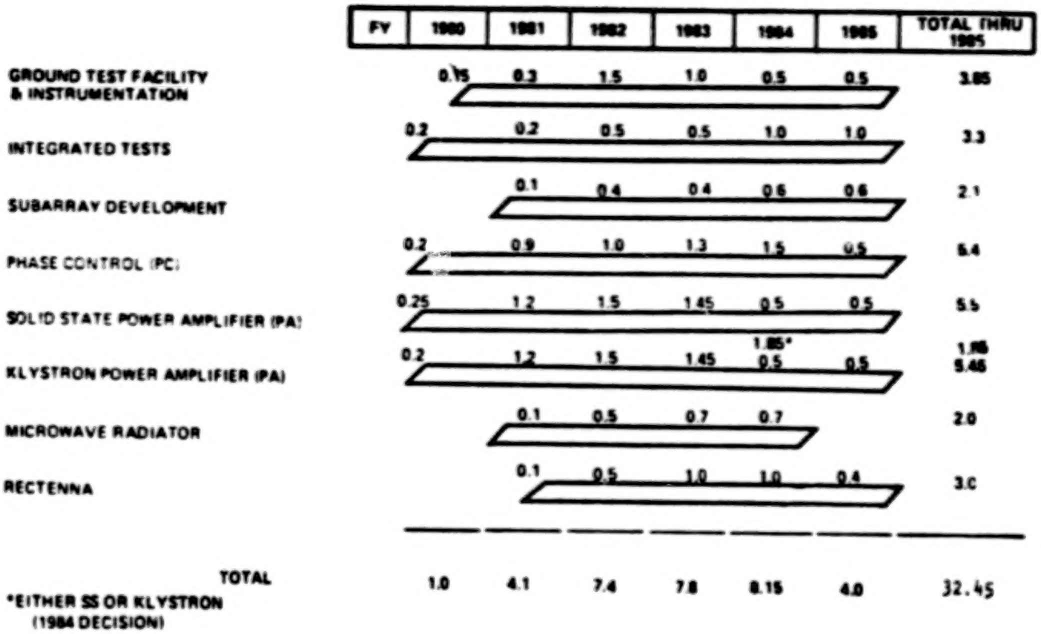


Figure 2.3-6. Exploratory Research Plan Cost
(Millions of Dollars - 1978)

costs by major project element, the anticipated scheduling, and major hardware delivery requirements. Funding begins in 1980 with one million for early development of the various microwave system elements and gradually builds to a peak year (1984) cost of slightly over eight million dollars (Figure 2.3-7) as the program reaches the system integration and test phase. Thereafter funding levels decrease to that required for an operations and test phase with no more large component buys anticipated.

Major project cost drivers are the phase control development and the parallel developments of the solid state and klystron power amplifiers. Together these three components account for over 50 percent of the total program cost.

Major ground rules and assumptions that form the basis of this cost estimate are:

1. Costs include design and development, production line tooling, prototypical hardware procurement, spares, test facilities, test instrumentation and test operations, and technology studies where applicable (phase control and power amplifiers). Use of some government facility and integration and the integrated tests with no charge.

2. All costs are in constant 1978 dollars (no allowance for post-1978 inflation).

3. Unit costs assumed: phase control - $100K, and power amplification - $50K.

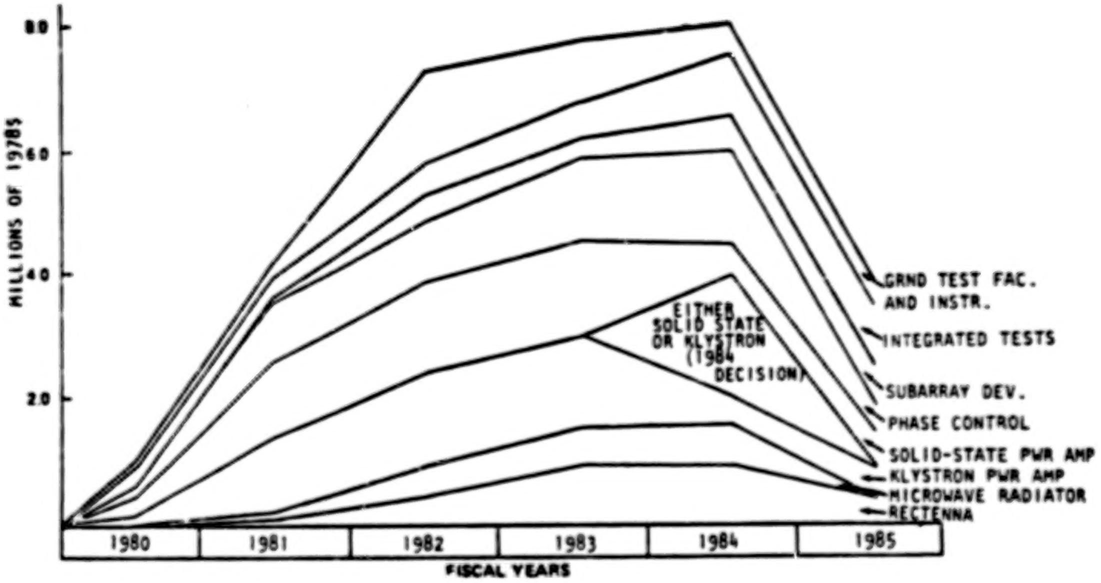


*Figure 2.3-7. Graph of Exploratory Research Plan Cost*

## 2.4 KEY TECHNOLOGY PLAN

The Exploratory Research Program described in the previous section has been prepared to evaluate the microwave power transmission system. While the microwave system is considered to be a very critical link in the SPS program, there are technology areas outside this link which will require attention in the 1981-85 time period to answer critical questions and establish credibility of the complete system concept. The Key Technology Program provides a summary of these additional technology studies. The Key Technology Program would consist of extended analysis, laboratory development, and ground tests in disciplines other than microwave. In addition, flight experiments and flight project definitions have been included. The term "flight experiments", as used herein, refers to orbital testing of components or elements of a system which can be completed in the 1981-85 period. Flight projects are broader in scope (usually system level activities) are more costly, and are not planned for completion until the 1986-90 period, since they require longer lead times for definition and planning.

During the past and current activities, elements of the SPS program have evolved based on trade results and more detailed refinement of concepts. It is therefore expected that this plan likewise will be continually refined as research proceeds. At present, however, it is believed that this plan encompasses those technology advancements which are needed to build upon past and current activities and provide new technical information on which to establish SPS program credibility and provide information on which to assess SPS program continuation.

The Key Technology Program will be directed toward laboratory development and testing of various elements to determine if the technical and performance assumptions of the earlier studies were valid; to obtain data for needed technical, economic, environmental, and societal assessments; to assess other SPS system/subsystem alternatives; and to conduct limited flight experiments and define flight projects. Key elements requiring such effort include extension of present terrestrial solar cell programs to space applications including processing techniques, annealing, and bonding; extensive computer analysis of large space structures; development and testing of graphite composites and thin-gage aluminum in the various required configurations; simulation and development of concepts and equipment of power distribution for steady state and transient performance; development and testing of space construction techniques for building of structural beams, fastening of structural members, installation of solar arrays and equipment; and development and demonstration of large electric thrusters utilizing argon and associated power processing equipment.

### 2.4.1 SOLAR ARRAY

The SPS reference system utilizes solar cells as the energy source for the satellite system. Two options have been carried for the reference system: (a) gallium aluminum arsenide (GaAlAs) solar cells, and (b) silicon (Si) solar cells. Each option represents a high degree of technology which has not been demonstrated.

Today's solar cells are less efficient, heavier, more costly, more susceptible to radiation damage, and produced in much smaller quantities than required for SPS. Currently, there are a number of ongoing solar cell development activities (DOE, DOD, NASA, etc.); however, none of these specifically address requirements for SPS. Since the solar blanket constitutes a significant portion of the SPS total program cost and mass, there is a need to develop solar cells suitable for SPS application.

The accomplishment of the following objectives is therefore deemed necessary:

- Develop the two solar cell materials baselined in the reference system.
- Assess and evaluate all candidate cells at end of development period.
- Assess susceptibility to degradation due to particulate radiation and investigate annealing.
- Examine approaches to automated solar cell fabrication and blanket assembly.
- Select reflector materials, develop test articles, and determine performance characteristics.
- Demonstrate 80 percent gallium recovery from bauxite.

The expected results of the solar array technology program are the development and selection of high performance, lightweight, low cost, radiation resistant and/or annealable solar cells with the ability to be processed and fabricated in large quantities at high yield. In addition, items which affect the array performance, such as reflectors, will be tested and evaluated for space environmental conditions.

A proposed program for early GaAs solar cell development is summarized in Appendix A.

### 2.4.2 POWER DISTRIBUTION

The Power Distribution Subsystem (PDS) as defined herein receives electrical power from the solar array blankets and provides the power busses, regulation, switching, circuit protection, and energy storage required to deliver regulated power for distribution to the antenna system (dc-RF converters) and the various subsystems (attitude control, information management, etc.). The grounding, electromagnetic interference control, high voltage plasma interactions, and spacecraft charging of the SPS are also included as part of the PDS.

The key technology needs are derived from the requirement to operate the PDS at thousands of volts to provide reasonable distribution efficiencies and low subsystem mass. The PDS must also provide acceptable safeguards for personnel and equipment and operate with reasonable reliability and maintainability. In certain key areas there is no applicable technology base from previous terrestrial or space programs which will permit confident extrapolation of SPS power distribution design and operational requirements. The SPS therefore requires technology advancement for a number of key elements in the PDS.

The current reference concept utilizes thin sheet aluminum conductors to optimize thermal and, in turn, electrical properties. It will be necessary to analyze and test materials, coatings, and geometric configurations capable of withstanding switching and fault transients as well as transients resulting from periodic Earth occultations.

Solid state power processors are visualized with the subsystem operating at thousands of volts and amps, whereas the current technology for transistors, thyristors, etc., is in the order of 1000 V at a few hundred amps. Therefore, technology for regulation and dc/dc conversion at the SPS design power levels need to be developed and demonstrated.

Subsystem switchgear is needed for power switching and circuit protection. Requirements placed on these type devices include switching and interrupting current levels of several thousand amps at the design voltage level of 40,000 V. Various types of switchgear have been developed for ground use which will handle these power levels. The gear is, however, large and bulky due to the requirement for "forced zero current," and not easily adaptable for space operation.

Spacecraft charging and plasma interaction studies must be initiated early to develop a better understanding of these phenomena and to derive restrictions imposed on the spacecraft design due to such things as identification of acceptable and unacceptable materials.

The expected results include the development of a math model simulation to initially define the subsystem and component requirements and later to simulate the expected subsystem performance characteristics based on integrated results from the component development activity. Laboratory development and testing will be conducted to confirm that suitable design approaches exist to achieve required SPS performance parameters for various critical components of the PDS. The design approach to, and technology of, thin sheet conductors will be demonstrated. The switchgear and power processor units will be designed and evaluated in a breadboard configuration. The slipring/brushes will be designed and scale assemblies will be evaluated. Plans and designs for a PDS technology breadboard facility will be available.

### 2.4.3 STRUCTURES AND CONTROL

The structural behavior, attitude control, and antenna pointing will have an influence on the pointing of the satellite, antenna, and ultimately, the microwave beam. The previous experience involving a combination of electronic and mechanical systems has been limited to much smaller systems than SPS. Structural and control systems will be intimately coupled in a new regime of low loads, high inertia, and low structural mass fraction. Since the impacts are economic, technical and safety in nature, it is important that these areas of uncertainity be better understood. Terrestrial testing of the structure/control interactions under simulated space conditions is not possible, thereby necessitating an unprecedented reliance on numerical simulation.

System design implications and improved estimates of achievable performance for structure and control systems, as well as microwave power beam pointing capabilities, are expected. Structural dynamic models will be developed to provide the analytical information needed for flight experiments through simulations of structural interactions with control systems, inertial loads, and thermal stresses and distortions. Identification of attitude control policies and techniques to minimize structural bending frequency constraints are expected. The techniques and policies developed will provide the capability for dynamic and static analysis of large structures with low mass fractions under modeled disturbances.

### 2.4.4 MATERIALS

The SPS should be designed for long lifetimes of approximately 30 years for economic reasons. The current understanding of Geosynchronous Earth Orbit (GEO) radiation effects on materials is very limited and related almost totally to film material or thermal control coatings. Spacecraft design for GEO operation is limited to several years. No data currently exist to evaluate the GEO radiation effects for many SPS candidate materials. One of the more serious material questions is that of the degradation of the resin systems if the graphite reinforced composite material is used. This type of material has desirable thermal characteristics, but its long term degradation characteristics are unknown. Long-life materials are also required for other subsystems such as solar array reflectors, thermal radiators for dc to RF converters, insulation, slipring brushes, etc.

Specific structural and special purpose materials (reflectors, thermal radiators, insulation, brush material, etc.) will be evaluated before and after exposure to simulated SPS environments (thermal cycling, vacuum, and radiation). Thermal control coatings and processing operations (joining, forming, etc.) will be analyzed in the experimental and analytical effort. Math models and approaches to accelerated testing will be developed and correlated with experimental data to minimize any future testing requirements.

The expected results include the examination of selected materials before and after exposure to simulate space environments and development of degradation models for use in design analysis calculations. This activity is expected to provide the technical foundation needed to select the more stable specific materials for further test and development.

### 2.4.5 CONSTRUCTION AND ASSEMBLY

Developing the capability for construction and assembly of very large low-density structures in space is an inherent requirement for the SPS program. The capability for installation of other subsystems (e.g., solar blankets, reflectors, power distribution lines and control equipment, microwave subarray hardware, etc.) on the structure must also be developed. New approaches for ground facilities (rectenna) construction and assembly must also be studied. Very little applicable data currently exist for this type of orbital and large scale terrestrial construction and assembly. Test data are needed to validate operational requirements and cost estimates.

The relatively high cost of flight testing requires accomplishing as much development as possible on the ground. Engineering evaluation of much of the critical beam builder design can be accomplished with ground tests using a 1-g beam builder configuration, special handling fixtures, an air bearing floor, and a water immersion facility. The beam builder development article is required to fabricate a long, continuous structural truss, allowing the evaluation of preprocessed materials packaging and dispensing; cap forming with heating, shaping, and cooling; synchronization and control of the truss elements; component handling and joining; and nondestructive quality control verification. Development of engineering and operational techniques for assembling more than one truss together to make a larger structural configuration can also be accomplished and simulated. Joint design and joining operations can be evaluated together with handling and assembly support equipment. These development tests will result in the engineering verification of a beam builder and associated assembly operations with sufficient confidence level to proceed to a flight verification experiment.

Ground development of assembly techniques for other than structural components will be initiated. Techniques for attaching hardware, such as solar blankets, reflectors, power distribution lines, thrusters, and microwave components will be pursued. The development of electrical connectors suitable for orbital assembly operations will be initiated.

Advanced automation techniques will be studied to determine more optimum approaches for the orbital assembly of SPS. These areas include: design studies of systems for advanced automation of space structural construction and assembly, programmable manipulators and terminal sensors, autonomous construction systems, machine vision and recognition, autonomous transfer systems, and others to be defined.

Construction and automation techniques will be studied for application to rectenna construction. Concepts will be developed and analyzed with costing parameters for inclusion in costing models.

### 2.4.6 TRANSPORTATION TECHNOLOGY

One of the key elements of the SPS concept is the transportation system since the large demonstration articles and operational satellites must be assembled and operated in space. For the SPS to be viable, the transportation system must be of high performance, relatively low cost, and environmentally acceptable. The technical approach includes investigations into the following areas.

Booster Engine Technology

The booster engine technology will focus on four primary areas:

Fuels Study. Various LOX/hydrocarbon propellants will be studied for applicability to the PLV and HLLV.

Engine Component Technology. The design and testing of cost effective engine components will be investigated. Design options will be studied which include gimbal techniques, throttling concepts, sensitivity to particulate contamination in propellants, and modular component designs.

Engine Operational Improvement. Perform bench tests of engine components or modules to provide engine operational improvements in acoustic and propellant emissions, lifetime characteristics, and repair/maintenance concepts.

Preliminary Engine System Design. Employ results from the research and technology efforts to provide engine design, performance and operational data in support of the PLV and HLLV definition.

### Electric Propulsion Technology

The electric propulsion technology will focus on three primary areas.

Thruster Development. The feasibility of large ion thrusters using argon will be developed. Characteristics of suitable SPS electrical thrusters will be established including thrust level, specific impulse, specific power, heat rejection requirements, total thrusting lifetime, and number of engine starts. Materials, engine electrical, thermal-structural and fluid-handling component development test will be conducted.

Power Conditioning Development. Static and dynamic breadboard and brassboard tests of conceptual designs for transforming solar array electrical output into the numerous regulated voltages necessary for the operation of ion bombardment electric propulsion systems will be conducted. The weight efficiency and unit cost of the flight design power conditioning apparatus will be confirmed.

Environmental Interactions. Basic research investigations of the interactions of internal and external current flows will be performed with simulated natural space and plasma environments and various dielectric geometries.

### Vehicle Technology

Preliminary design studies will be conducted to define the technology required for large, fully reusable launch vehicle systems with particular emphasis on multiuse thermal protection systems, propulsion systems, structures/materials, aerothermal, design, and integrated propulsion/configuration design.

### Orbital Storage and Transfer of Propellants

The feasibility of the storage and transfer of cryogenic propellants on-orbit will be established.

## 2.4.7 FLIGHT EXPERIMENTS AND PROJECT DEFINITION

A basic development concept embodied in this plan is that most of the Key Technology Program, in support of key issue resolution, can be accomplished through comprehensive analysis, and ground experimentation and development. There is, however, a requirement for component level orbital verification testing to address issues that could not otherwise be resolved. The exclusion of these flight experiments would not only jeopardize the credibility of SPS but could in the long run require greater funding for SPS development. In addition to analysis, ground tests, and component level flight tests, some system-level orbital tests will be necessary for adequate demonstration of SPS concept feasibility. The complexity of these tests is such that detailed definition and planning must be initiated early in the Key Technology Program to assure test results by 1990.

With regard to early Shuttle orbital tests the objectives and requirements of each experiment will be defined in detail. Shuttle interfaces and other orbital support requirements will be defined. Relationships to other experiments will be examined for possible common support requirements. Designs will be developed. Flight test hardware will be fabricated if precursor ground test articles cannot be used; where possible, ground test hardware will be designed to meet flight requirements. Flight tests will be carried out. This task will include the following experiments:

- Materials Test - Expose candidate materials to the ultraviolet, particulate radiation, and plasma environment of GEO.
- Construction and Assembly - Orbital construction and assembly demonstration which includes fabrication of beam elements, handling of structural members, and assembly of a small demonstration article.
- Microwave Component Test - Operational exposure of microwave components to the LEO environment to determine the impact on performance characteristics.

The flight projects definition task will produce detailed definition and planning for SPS flight projects which are to be accomplished during the 1986-90 period. Level of definition will be through Phase B studies.

The objectives and requirements of each project will be defined in detail. Preliminary payload designs will be developed. Shuttle interfaces will be defined. Requirements for other orbital support facilities will be identified and preliminary designs for these facilities developed. Costs and schedules will be defined for each project and for any required orbital support facilities. The following potential projects are included:

- Construction and Assembly - Fabrication in orbit of a large structure, requiring orbital manufacturing, and assembly of large, lightweight structural members and attachment of subsystem elements.
- LEO Integrated Microwave Tests - A LEO demonstration of microwave subsystem.
- GEO Inverted Microwave Transmission - Test article in GEO which includes pilot beam transmission from the satellite to ground while receiving microwave energy from a ground based microwave array.
- Solar Array - Integrated solar array and power distribution system test which could be included in the above projects.

### 2.4.8 KEY TECHNOLOGY PLAN COSTS

A top level summary of the development activities and funding requirements covered in the plan are presented in Figure 2.4-1. The technology development activities which are to be initiated in 1981 and their associated funding requirements are summarized in the Table 2.4-1.

| KEY TECHNOLOGY AREAS | FY81 | FY82 | FY83 | FY84 | FY85 | TOTAL |
|---|---|---|---|---|---|---|
| SOLAR ARRAY | 2000 | 3000 | 3500 | 3500 | 3000 | 15000 |
| | CELL DEV /ANNEALING/ PRODUCTION PROCESSING/ GALLIUM RECOVERY | | | | | |
| POWER DISTRIBUTION | 400 | 800 | 1600 | 1200 | 1000 | 5000 |
| | COMPUTER SIMULATIONS/ COMPONENT BREADBOARD | | | | | |
| STRUCTURES AND CONTROL | 300 | 900 | 1200 | 1300 | 800 | 4500 |
| | MODELING & CONTROL TECHNIQUE DEV | | | | | |
| MATERIALS | 200 | 800 | 1600 | 1600 | 1000 | 5200 |
| | GROUND TEST / DEGRADATION MODEL DEV | | | | | |
| CONSTRUCTION AND ASSEMBLY | 700 | 1300 | 1700 | 1800 | 1000 | 6500 |
| | GROUND SIMULATIONS/ASSEMBLY TECHNIQUES & EQUIPMENT DEV | | | | | |
| TRANSPORTATION | 800 | 1300 | 2000 | 3000 | 2900 | 10000 |
| | DEFINITION STUDIES/BOOSTER & ION ENGINE DEV/VEHICLE DESIGN STUDIES | | | | | |
| FLIGHT EXPERIMENTS | 2000 | 5000 | 7000 | 8000 | 6000 | 28000 |
| | PAYLOAD DEFINITION/KEY SHUTTLE SORTIE FLIGHTS | | | | | |
| FLIGHT PROJECT DEFINITION | 800 | 1200 | 2500 | 3000 | 4500 | 12000 |
| | PRELIMINARY DEFINITION/PHASE A & B STUDIES | | | | | |
| TOTAL<br>FUNDING (THOUSANDS OF 1978 DOLLARS) | 7100 | 14400 | 21000 | 23500 | 20200 | 86200 |

*Figure 2.4-1. Key Technology Program Summary*

*Table 2.4-1. Key Technology Program - 1981 Starts*

| KEY TECHNOLOGY | FUNDING (THOUSANDS OF 1978 DOLLARS) |
|---|---|
| SOLAR ARRAY | 2000 |
| GaAlAs CELL DEVELOPMENT<br>SILICON CELL DEVELOPMENT<br>ASSESSMENT OF ALL CANDIDATE CELLS | |
| POWER DISTRIBUTION | 400 |
| COMPUTER SIMULATION TO IDENTIFY POWER DISTRIBUTION SUBSYSTEM REQUIREMENTS<br>DESIGN OF POWER CONDUCTORS<br>SPACECRAFT CHARGING SIMULATION | |
| STRUCTURES AND CONTROL | 200 |
| ASSESSMENT TO IDENTIFY CONSTRAINTS<br>CONTROL POLICIES AND TECHNIQUES DEVELOPMENT | |
| MATERIALS | |
| CANDIDATE MATERIAL SELECTION AND GROUND TESTING | |
| CONSTRUCTION AND ASSEMBLY | 700 |
| GROUND SIMULATIONS<br>SPS BEAM BUILDER TECHNOLOGY DEVELOPMENT | |
| TRANSPORTATION | 800 |
| BOOSTER ENGINE TECHNOLOGY<br>ELECTRIC THRUSTER TECHNOLOGY | |
| FLIGHT EXPERIMENTS | 2000 |
| REQUIREMENTS/PRELIMINARY DEFINITION | |
| FLIGHT PROJECT DEFINITION | 800 |
| TOTAL | 7100 |

## 2.5 ORBITAL TEST VERIFICATION PHASE

An essential requirement exists for major SPS subsystem test and evaluation at LEO and geosynchronous altitude late in the 1980's. Current NASA planning projects a major SPS subscale test article for LEO-to-LEO microwave testing. This same test platform can be boosted via electric propulsion to GEO to serve as an SPS multitest platform in both a GEO-to-ground and ground-to GEO mode (functioning as an inverted test range with the addition of pilot beam electronics).

### 2.5.1 SPS TEST PLATFORM EVOLUTION

It appears likely that SPS orbital test requirements and test system definition will have to be satisfied through the evolutionary utilization of NASA large structure space projects that evolve and are funded. Requirements for multimission applicability, construction modularity, and a broad range of power, size, and mass options, which include SPS test verification objectives, will need to be evaluated and synthesized. The degree to which SPS technical issues are resolved will be a function of the commonality between developments in large space structures/large power modules (LSS/LPM) and the characteristics of the final SPS system.

The configuration of the proposed large space power platform can be considered indeterminate at this point in time and will emerge as a product of the Large Space Structures technology program and/or the SEP/PEP/OSM power module development thrust as shown in Figure 2.5-1.

This large orbital power platform can be effectively utilized for SPS orbital verification testing in both LEO and GEO. The early development of GaAs-CR2 solar array technology is a key determinant in the definition of the orbital test platform.

Figure 2.5-2 summarizes the possible evolution of the SPS multi-test platform. Two developmental paths reflect (1) a high-legacy large orbital test system and (2) an alternative low-cost geosat system for early environmental and inverted test range evaluations. Both silicon and GaAs solar array options could be available to space system developments.

Figure 2.5-3 summarizes the principal system characteristics that could be achievable for LSSP and SEP/PEP derivatives of an SPS orbital development test article. With respect to the extent to which these development options satisfy initial verification objectives of SPS technology, the issues involve the following:

- Beam machine space fabrication versus deployable/erectable construction

- Silicon solar arrays versus GaAs solar arrays versus hybrid array combinations

- Capability for both LEO and GEO test operations

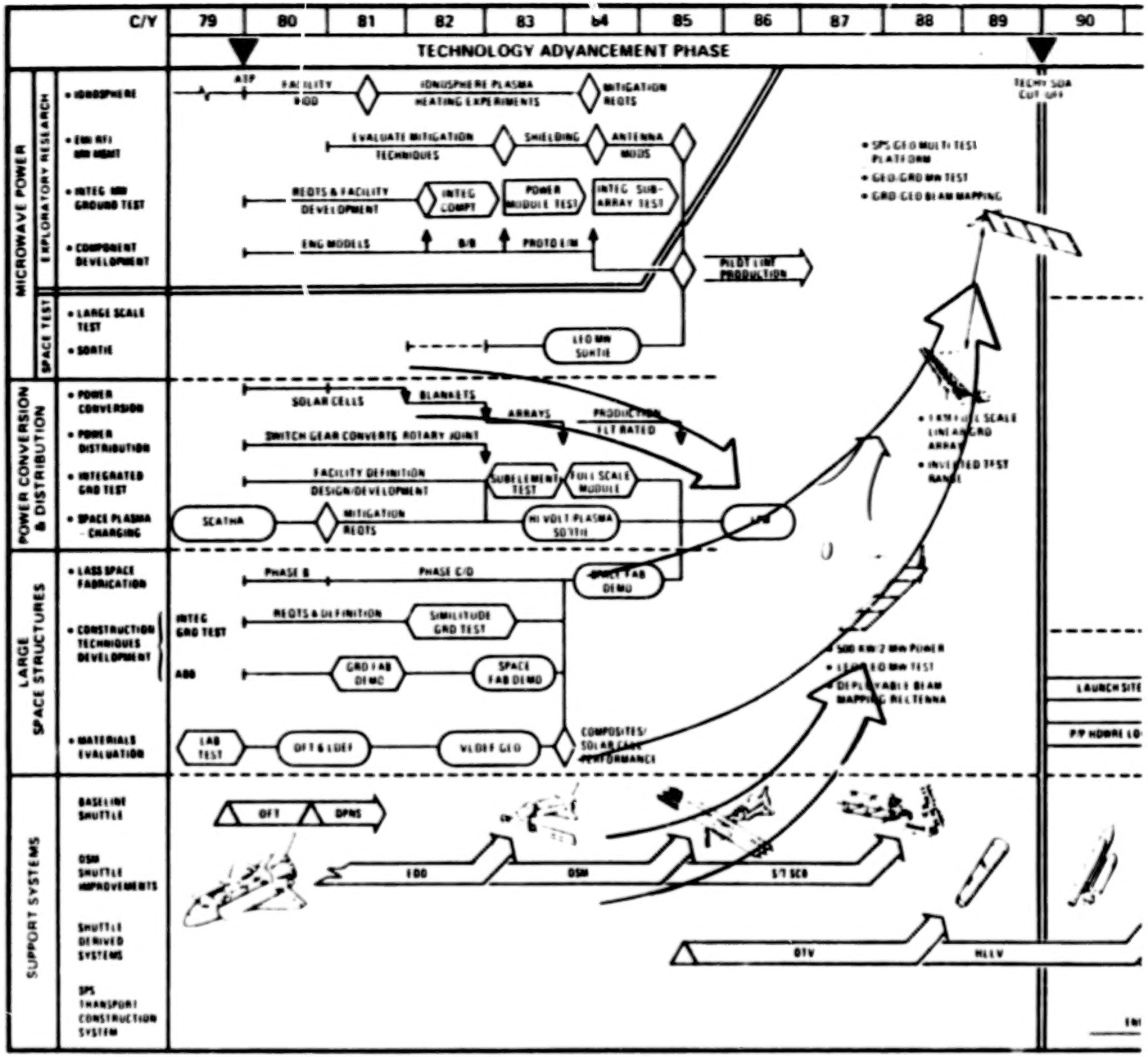

C/Y
79
80
81
82
83
84
85
86
87
88
89
90
TECHNOLOGY ADVANCEMENT PHASE
MICROWAVE POWER
EXPLORATORY RESEARCH
• IONOSPHERE
ATP
FACILITY
MOD
IONOSPHERE PLASMA
HEATING EXPERIMENTS
MITIGATION
REQTS
• EMI RFI
MW MGMT
EVALUATE MITIGATION
TECHNIQUES
SHIELDING
ANTENNA
MODS
• INTEG MW
GROUND TEST
REQTS & FACILITY
DEVELOPMENT
INTEG
COMPT
POWER
MODULE TEST
INTEG SUB-
ARRAY TEST
• COMPONENT
DEVELOPMENT
ENG MODELS
B/B
PROTO EM
PILOT LINE
PRODUCTION
SPACE TEST
• LARGE SCALE
TEST
• SORTIE
LEO MW
SORTIE
POWER CONVERSION
& DISTRIBUTION
• POWER
CONVERSION
SOLAR CELLS
BLANKETS
ARRAYS
PRODUCTION
FLT RATED
• POWER
DISTRIBUTION
SWITCH GEAR CONVERTS ROTARY JOINT
• INTEGRATED
GRD TEST
FACILITY DEFINITION
DESIGN/DEVELOPMENT
SUBELEMENT
TEST
FULL SCALE
MODULE
• SPACE PLASMA
- CHARGING
SCATHA
MITIGATION
REQTS
HI VOLT PLASMA
SORTIE
LARGE
SPACE STRUCTURES
• LASS SPACE
FABRICATION
PHASE B
PHASE C/D
SPACE FAB
DEMO
• CONSTRUCTION
TECHNIQUES
DEVELOPMENT
INTEG
GRD TEST
REQTS & DEFINITION
SIMILITUDE
GRD TEST
ADD
GRD FAB
DEMO
SPACE
FAB DEMO
• MATERIALS
EVALUATION
LAB
TEST
OFT & LDEF
VLDEF GEO
COMPOSITES/
SOLAR CELL
PERFORMANCE
TECHY SDA
CUT OFF
• SPS GEO MULTI TEST
PLATFORM
• GEO/GRD MW TEST
• GRD GEO BEAM MAPPING
• FULL SCALE
LINEAR GRD
ARRAY
• INVERTED TEST
RANGE
• 500 KW/2 MW POWER
• LEO/LEO MW TEST
• DEPLOYABLE BEAM
MAPPING RECTENNA
LAUNCH SITE
P/P HDWRE LO
SUPPORT SYSTEMS
BASELINE
SHUTTLE
OFT
OPNS
OSM
SHUTTLE
IMPROVEMENTS
EOD
OSM
S/T SCB
SHUTTLE
DERIVED
SYSTEMS
OTV
HLLV
SPS
TRANSPORT
CONSTRUCTION
SYSTEM

*Figure 2.5-1. SPS Technology Advancement Plan*

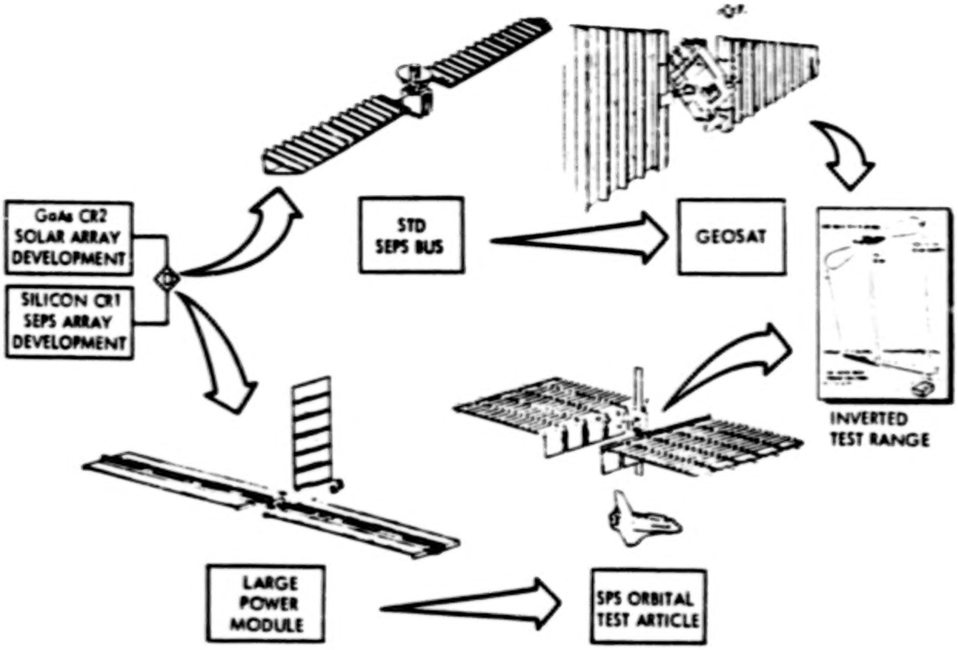
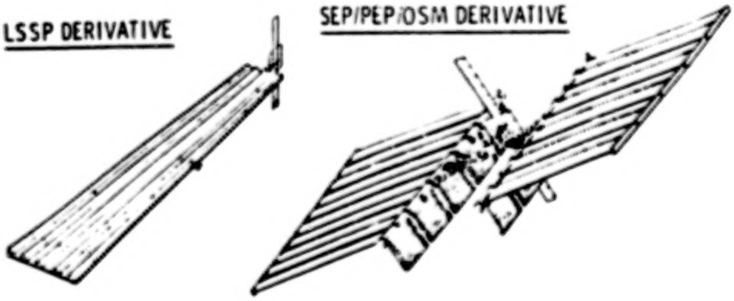

GaAs CR2 SOLAR ARRAY DEVELOPMENT
SILICON CR1 SEPS ARRAY DEVELOPMENT
STD SEPS BUS
GEOSAT
INVERTED TEST RANGE
LARGE POWER MODULE
SPS ORBITAL TEST ARTICLE

Figure 2.5-2. SPS Multi-Test Platform Evolution



| | LSSP DERIVATIVE | SEP/PEP/OSM DERIVATIVE |
|---|---|---|
| • POWER CONVERSION | ✓ COULD BE ALL GaAs OR HYBRID | ✓ SEP SILICON ROLL-OUT ARRAY - COULD BE HYBRID |
| • POWER DISTRIBUTION | ✓ DESIGN OPTIMIZED FOR LEO & GEO HI-VOLTAGE OPERATION | ✓ OPTIMIZED FOR LEO OPERATION ≈ 200 VOLTS |
| • STRUCTURE | ✓ PROTOTYPICAL BEAM MACHINE FABRICATION/JOINING | ✓ DEPLOYABLE ARRAYS - ERECTABLE ANTENNA |
| • POWER TRANSMISSION | ✓ MEDIUM POWER AMPLIFIERS | ✓ MEDIUM POWER AMPLIFIERS |
| • DEGREE OF SPS VERIFICATION | ✓ HIGHEST | ✓ MODERATE |
| • PROBABILITY OF EARLY IMPLEMENTATION | ✓ MODERATE | ✓ HIGHEST |

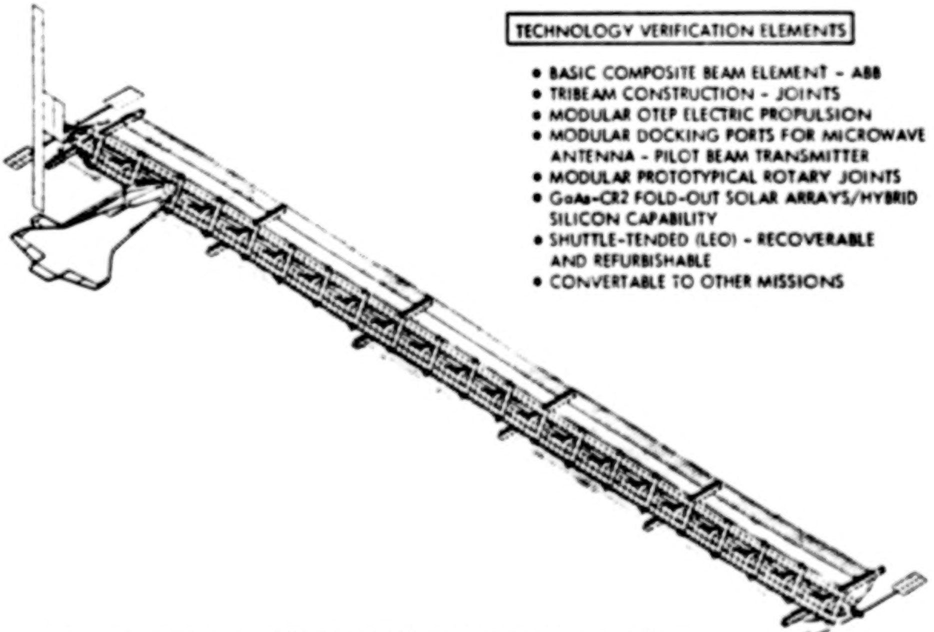
Figure 2.5-3. SPS Test Platform Comparative Characteristics

An SPS test article evolving out of the large space structures program with beam machine construction is likely to provide the highest degree of SPS technology verification for subsystems other than the MPTS. If the SPS system is baselined for GaAs solar cells, the LSSP derivative again provides the best technology verification results if an intensive GaAs solar array development program is initiated by FY 1980. Characteristics of the microwave power amplifier will be determined during the microwave exploratory research program and will drive the microwave antenna design configuration.

A mandatory development requirement for SPS technology verification, leading to technical readiness by 1990, is the need for geosynchronous environmental testing of integrated, prototypical SPS subsystems. This requirement can be satisfied by transferring the proposed LEO subscale test article to GEO by a self-contained electric propulsion system, to be used as the test vehicle for verification of the solar array, power distribution, and control subsystems. This offers the opportunity to perform integrated LEO tests, orbit transfer radiation degradation evaluations of solar cells and reflectors, and long-duration operational tests of solar array and power conversions, distribution, and control as a system supplying the multiple required voltages at the klystrons. An additional benefit from this approach is the flexibility of payload return to earth.

### 2.5.2 SPS LEO/GEO MULTI-TEST PLATFORM CONCEPT

A representative Large Space Structures Program derivative of an optimized orbital test article with high SPS legacy has been conceptualized as shown in Figure 2.5-4. This configuration was developed to meet the following requirements.



**TECHNOLOGY VERIFICATION ELEMENTS**

- BASIC COMPOSITE BEAM ELEMENT - ABB
- TRIBEAM CONSTRUCTION - JOINTS
- MODULAR OTEP ELECTRIC PROPULSION
- MODULAR DOCKING PORTS FOR MICROWAVE ANTENNA - PILOT BEAM TRANSMITTER
- MODULAR PROTOTYPICAL ROTARY JOINTS
- GaAs-CR2 FOLD-OUT SOLAR ARRAYS/HYBRID SILICON CAPABILITY
- SHUTTLE-TENDED (LEO) - RECOVERABLE AND REFURBISHABLE
- CONVERTABLE TO OTHER MISSIONS

*Figure 2.5-4. SPS LEO/GEO Multi-Test Platform (High SPS Legacy)*

1. Tribeam construction, using space fabricated composite beams.
2. Solar electric propulsion system for later ascent to higher earth orbit.
3. Microwave antenna with adequate power to perform SPS Flight Demonstration of in-space transmission, to test:
    - a) Wave lobe quality at 16.5 km
    - b) Maximum heating condition
4. Antenna to be powered by either CR-1 standard silicon SEPS array blankets or advanced technology standardized GaAs CR-2 foldout array blankets.
5. Low earth orbit construction, using Shuttle orbiter.
6. SPS test to be conducted initially in low earth orbit, then transferred to GEO.
7. Capability for conversion to distributed chemical thrusters or to interim upper stage (concentrated) propulsion system.
8. Design for legacy, applicability in national space program.

The proposed test article can be constructed in LEO with less than 5 Shuttle flights.

The basic tribeam structure detail is shown in Figure 2.5-5. The concept design logis is summarized below:

| Feature | Reason/Basis |
|---|---|
| • Tribeam Configuration | • Legacy for SPS, other large tribeam concepts<br>  • Joining<br>  • Handling<br>  • Wiring<br>  • End Fittings<br>  • Construction Fixture on Orbiter<br>  • Applicability - Does Job |
| • Over Hang Cross Beams for attaching Solar Blankets | • Reduces weight of tribeam structure<br>• Not necessary that all cross beams be same length |
| • Size of Tribeam vs Cross Beam for Solar Array<br>  • 20 meter wide major cross beams<br>  • 4.3 meter tribeam legs<br>  • A large variety of methods and equipment can be used to build candidates (size alone does not dictate) | • Multiples of General Dynamics composite beam bay spacing<br>• Trade: Weight and column strength for potential growth<br>• Compatible with RMS reach from Orbiter (50')<br>• 20m width permits 200m length for favorable access ratio<br>• 20m width compatible with five, 4m wide solar blankets (per standard SEPS Solar Array) |

| Feature | Reason/Basis |
|---|---|
| • RCS Pods Location<br>• Corners of solar array<br>• Ends of major cross beams | • Provides large moment, minimizes thrust, fuel weight<br>• Minimizes plume impingement on solar array, while utilizing available structure<br>• Facilitates retrofit for later purposes |

Modular docking provisions are illustrated in Figure 2.5-6 and include three docking ports as described below:

| Feature | Reason/Basis |
|---|---|
| • Docking Ports | |
| • Orbiter revisit: Location near antenna on ridge of tribeam opposite solar array | • Near to vehicle C.G.<br>• Close to area of expected major retrofit (antenna, SEPS)<br>• Compatible with use of construction fixture |
| • Between slipring/rotary joint and solar array. Both ends of tribeam | • Slipring/rotary joint is major mass/volume item, probably brought up on later flight<br>• Facilitates retrofit or replacement of mechanical devices, SEPS thrusters, antenna packages<br>• Docking ports aligned with major mass axis of vehicle. |
| • Between antenna and SEPS thruster/slipring rotary joint | • Facilitates retrofit of antenna/sensor following SPS test phase<br>• Antenna is major, massive installation, probably on later Shuttle flight |

Design characteristics of the proposed SPS test article microwave antenna are shown in Figure 2.5-7. The antenna consists of a 9m × 9m thermal test subarray and a 44m long linear phase control array. The antenna is designed to fit into the Shuttle cargo bay and be deployed in LEO as shown in Figure 2.5-8. The total array utilizes 279 1-kW power amplifiers. The rotary joint and dc/dc converter subsystems are integral with the antenna.

### 2.5.3 SPS GEOSAT PLATFORM OPTION

There are competing options for GEO utilization of the proposed LEO large power platform as shown in Figure 2.5-9. The billion dollar investment required for a large space power platform will preclude multiple vehicles and drive space facility utilization toward optimum LEO applications for space power, construction support and space industrialization projects.

If the large space power platform will not be available for geosynchronous service, an alternate SPS option is utilization of a minimum-cost GEO multi-test satellite. This geosat system would be a single wing element of the large power module with a power level of about 100 kW and would perform as the geosynchronous element of the ground to GEO inverted test range.

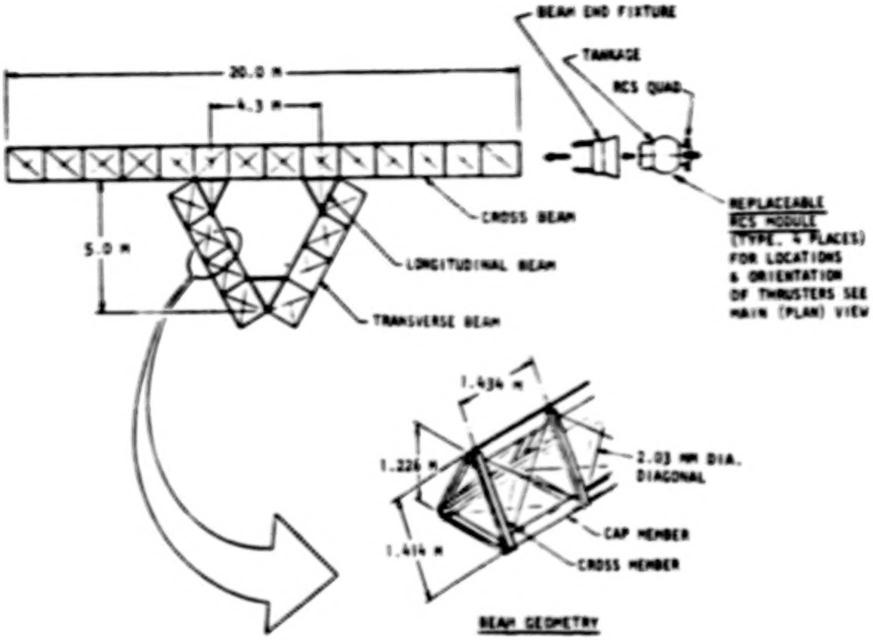

BEAM END FIXTURE
TANKAGE
RCS QUAD
20.0 M
4.3 M
5.0 M
CROSS BEAM
LONGITUDINAL BEAM
TRANSVERSE BEAM
REPLACEABLE RCS MODULE (TYPE. 4 PLACES) FOR LOCATIONS & ORIENTATION OF THRUSTERS SEE MAIN (PLAN) VIEW
1.434 M
1.226 M
1.414 M
2.03 MM DIA. DIAGONAL
CAP MEMBER
CROSS MEMBER
BEAM GEOMETRY

Figure 2.5-5. Tribeam Structure Detail

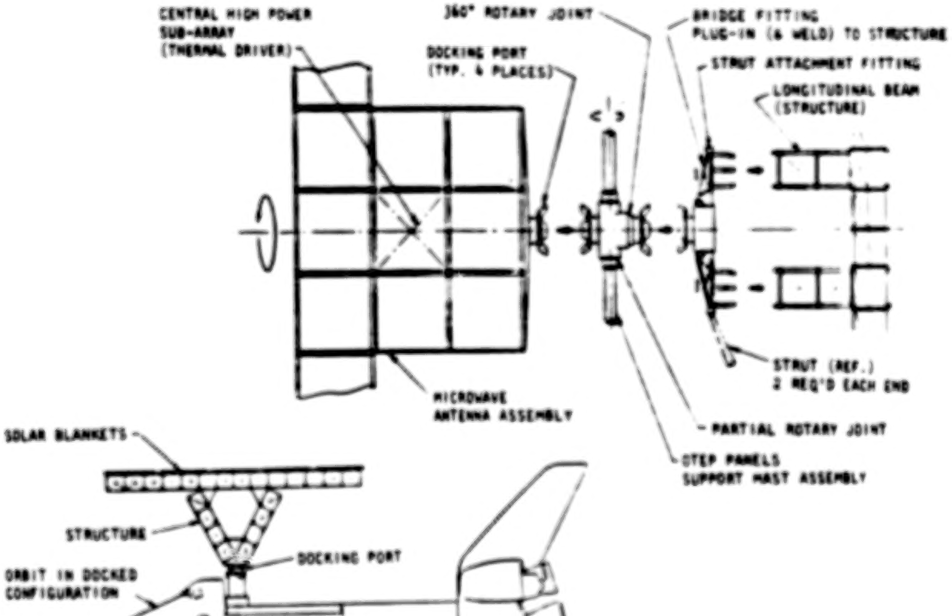
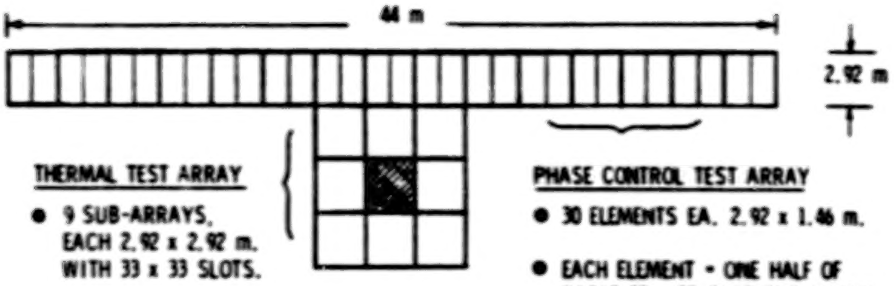

CENTRAL HIGH POWER SUB-ARRAY (THERMAL DRIVER)
360° ROTARY JOINT
DOCKING PORT (TYP. 4 PLACES)
BRIDGE FITTING PLUG-IN (& WELD) TO STRUCTURE
STRUT ATTACHMENT FITTING
LONGITUDINAL BEAM (STRUCTURE)
STRUT (REF.) 2 REQ'D EACH END
MICROWAVE ANTENNA ASSEMBLY
PARTIAL ROTARY JOINT
OTEP PANELS SUPPORT MAST ASSEMBLY
SOLAR BLANKETS
STRUCTURE
DOCKING PORT
ORBIT IN DOCKED CONFIGURATION

Figure 2.5-6. Modular Docking Provisions



**THERMAL TEST ARRAY**

- 9 SUB-ARRAYS, EACH 2.92 x 2.92 m. WITH 33 x 33 SLOTS.
- 8 OUTER SUB-ARRAYS HAVE 16 KLYSTRONS EACH 1 kW OUTPUT
- CENTRAL SUB-ARRAY HAS 121 ONE kW TUBES
- TOTAL RF POWER 16 x 8 + 121 = 249 kW

**PHASE CONTROL TEST ARRAY**

- 30 ELEMENTS EA. 2.92 x 1.46 m.
- EACH ELEMENT = ONE HALF OF BASIC 33 x 33 SLOT SUB-ARRAY HAVING EITHER 33 x 16 OR 33 x 17 SLOTS (ALTERNATING).
- SINGLE 1 kW KLYSTRON PER ELEMENT. TOTAL RADIATED RF POWER 30 kW.

- ALUMINUM WAVEGUIDE .05 cm (.020 in) WALL: TOTAL MASS 970 kg.

*Figure 2.5-7. SPS Test Article Antenna*

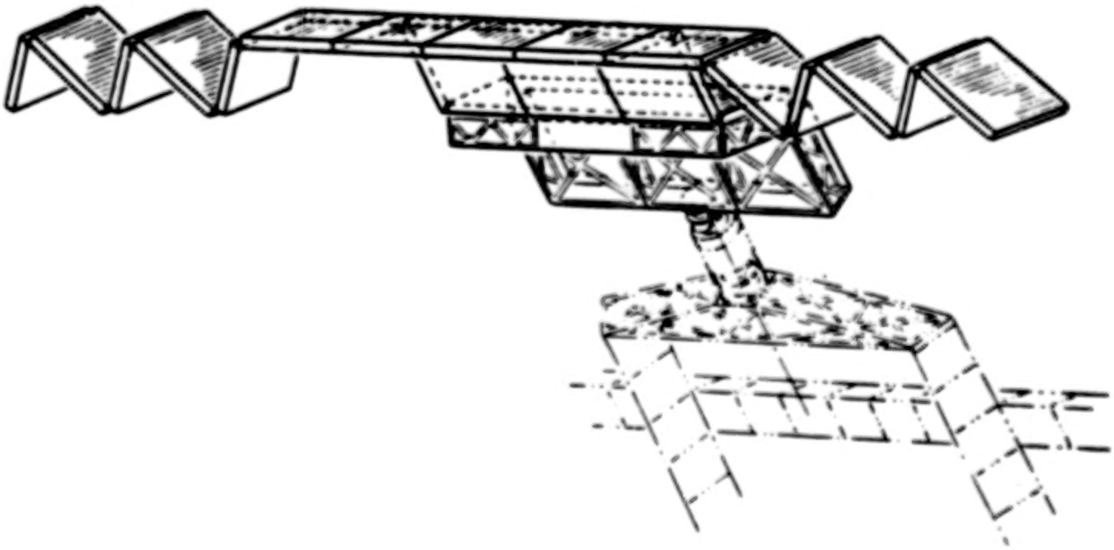
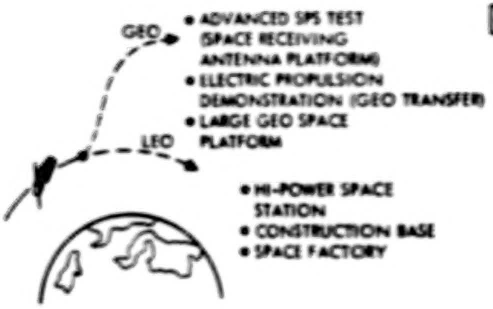


*Figure 2.5-8. Microwave Antenna Deployment*


GEO
• ADVANCED SPS TEST (SPACE RECEIVING ANTENNA PLATFORM)
• ELECTRIC PROPULSION DEMONSTRATION (GEO TRANSFER)
• LARGE GEO SPACE PLATFORM
LEO
• HI-POWER SPACE STATION
• CONSTRUCTION BASE
• SPACE FACTORY

**• A LOW-COST ALTERNATIVE**

✓ LOW POWER ( ≈100 KW) SINGLE WING MODULE OF LPM OR SEPS

✓ SEPS DEDICATED GEO TEST VEHICLE

✓ PERFORMS 3 FUNCTIONS

- ORBITAL TRANSFER & PROPULSION TESTS
- PILOT BEAM/BEAM MAPPING END OF INVERTED TEST RANGE
- COMPONENT ENVIRONMENTAL TEST BED

**• CONSIDERATIONS**

✓ ONLY ONE LPM - $1B

✓ COMPETING LEO MISSION OPTIONS

✓ LPM OPTIMIZED FOR LEO POWER LEVELS

✓ AVAILABILITY FOR SPS LONG-TERM GEO USE MAY BE LIMITED OR TOO LATE

**• SYSTEM LIMITATIONS**

✓ PRIMARILY PILOT BEAM & BEAM MAPPING FUNCTIONS

✓ COMPONENT LEVEL ENVIRONMENTAL TESTING ONLY - LOW POWER

✓ LOW LEGACY FOR SPS STRUCTURES

✓ LIMITED ALTERNATIVE MISSION USE

*Figure 2.5-9. SPS GEO Test Platform Options*

A GaAs solar array version of a low-cost SPS geosat spacecraft is shown in Figure 2.5-10. It can be a derivative of the SEPS/OTV vehicle either as a dedicated modified system or as a hybrid system using a standard SEPS bus with a dedicated SPS multi-test payload for geosynchronous environmental tests and inverted range microwave phase control demonstrations.

This proposed GEO multi-test platform would function as the geosynchronous element of a ground-to-GEO inverted microwave test range, as shown in Figure 2.5-11. A ground-based, one-kilometer linear transmitting antenna, one power module in width, is proposed for full-scale phase control testing. Full-scale aperture testing is required to verify phase control linearity and array performance prior to commitment of major space antenna construction effort. The pilot-beam element of the orbital system illuminates the ground antenna linear array where the beam is received by the line source retro-electronics which, in turn, phase the line source to return its beam to the satellite. The beam is a fan beam since the line source aperture is a full-scale, one kilometer in the east-west direction, but only one power module wide ( 1 m) in the north-south direction. A beam-mapping piggyback sub-satellite operates in a free-flying mode and probes the beam pattern by controlled drifting in an east-west pattern.

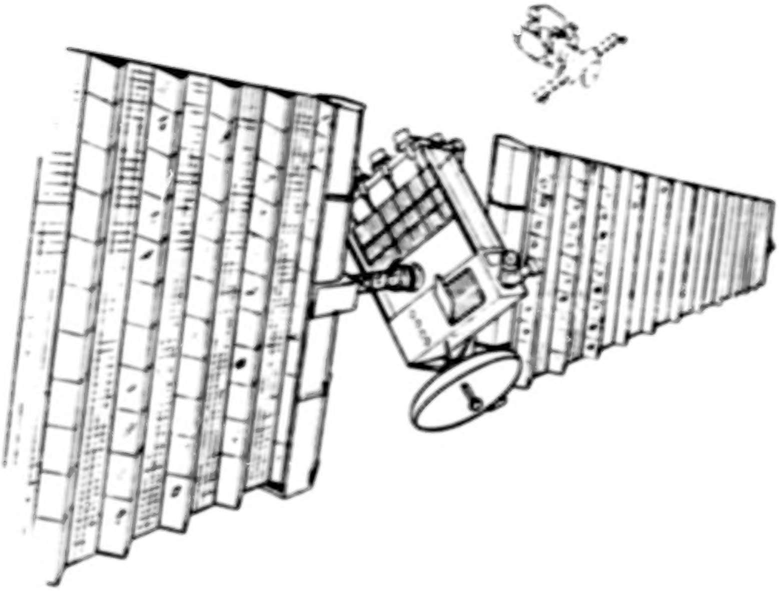
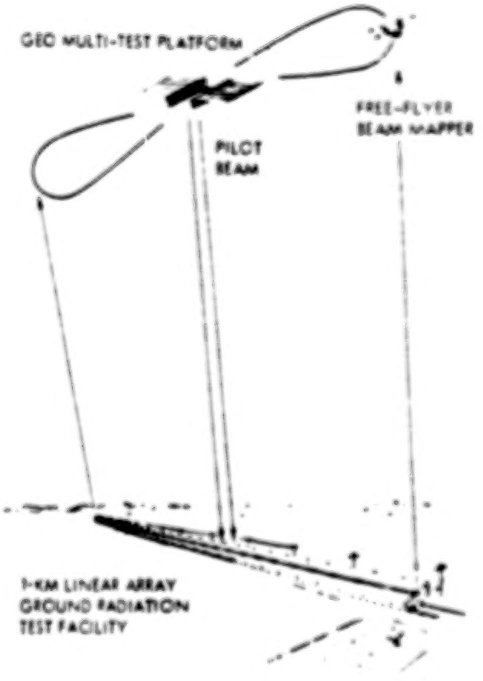


Figure 2.5-10. Low-Cost SPS GEO Multi-Test System


GEO MULTI-TEST PLATFORM
FREE-FLYER BEAM MAPPER
PILOT BEAM
1-KM LINEAR ARRAY GROUND RADIATION TEST FACILITY

OBJECTIVES

- TEST PERFORMANCE OF RETROELECTRONICS USING FINAL APERTURE
- DETERMINE MANUFACTURING TOLERANCES FOR RETROELECTRONICS
- DETERMINE ATMOSPHERE EFFECTS
- TEST EFFECT OF TRANSIENTS
- POWER DENSITY PROFILE MEASUREMENTS

GRTF CHARACTERISTICS

- GROUND ANTENNA INSTALLATION
  - ✓ 1-KM EAST-WEST LINE SOURCE SIZE
  - ✓ ONE POWER MODULE WIDE     RADIATES 50 KW
  - ✓ PROTO MODULAR MPTS ELEMENTS/PHASE CONTROL
- SPS ORBITAL MULTI-TEST PLATFORM
  - ✓ INTEGRATED GEOSYNC ORBITAL TEST SYSTEM
  - ✓ SYSTEM ELEMENTS
    - PROTO 500-W PILOT BEAM
    - BEAM MAPPER SUBSATELLITE
    - MODULAR SOLAR ARRAYS
    - SCALED POWER CONVERSION — POWER DISTRIBUTION SUBSYSTEMS
    - EOTV PROPULSION SYSTEM FOR ORBITAL TRANSFER & RETURN
    - MPTS SUBSYSTEM TEST ELEMENTS

Figure 2.5-11. SPS GEO Multi-Test Platform - Inverted Test Range

# 3.0 PILOT PLANT DEMONSTRATION PHASE

Completion of the SPS Technology Advancement phase of SPS development by 1990 will provide the technical confidence to proceed with the full-scale pilot-plant demonstration phase. The primary objective of this development phase is to demonstrate commercial viability of the SPS system to those utility firms and consortiums that would ultimately capitalize and operate the production system. The proposed pilot-plant demonstration program, as shown in Figure 3.0-1, reflects in general the "precursor" demonstration concept proposed as the most cost-effective approach to demonstration of large-scale pilot-plant commercial end-to-end performance.

## 3.1 PILOT PLANT CONSTRUCTION SCENARIO

The precursor satellite would be constructed in LEO, by using Shuttle-derived mass transfer and construction support systems, and transferred to geosynchronous orbit by a dedicated electric-propulsion system. It would operate in the same mode as the full-scale satellite by directing a microwave power beam at a power level of several hundred megawatts to a standard modular segment of the proposed operational ground rectenna. The demonstration/operational period would range from six months to several years, during which time the majority of the principal SPS elements of the full-scale solar power satellite would be operated in the in-situ environment. Operational data would provide the quantitative basis for analyses which would support full SPS commercial capability.

The current SPS operational system construction guideline calls for satellite construction in geosynchronous orbit, with an SPS electric orbital transfer vehicle (EOTV) baselined to provide construction material mass transfer from LEO to GEO. A primary guideline for SPS pilot plant development involves the utilization of this EOTV as the power module. This allows common development and construction utilizing a single modular construction facility that can be expanded into the basic SPS assembly fixture. An evolutionary construction scenario is illustrated in Figure 3.1-1 wherein the basic construction facility is fabricated in LEO and utilized in low orbit to construct first the pilot plant and then the operational EOTV's. The construction facility would then be upgraded to SPS production capability and transferred to GEO by the EOTV.

The initial step is establishment of a LEO base as shown in the lower left of the chart. Crew and power modules are transported to LEO by Shuttle derivatives and assembled. When the base is fully operational, Shuttle external tanks are delivered and mated to form construction fixtures for SCB construction. Since the more economical HLLV will not be available and since overall plans specify an EOTV test vehicle, only the center trough of the SCB would be constructed initially. This trough would be used to fabricate the pilot plant EOTV with antenna. After proof of concept and

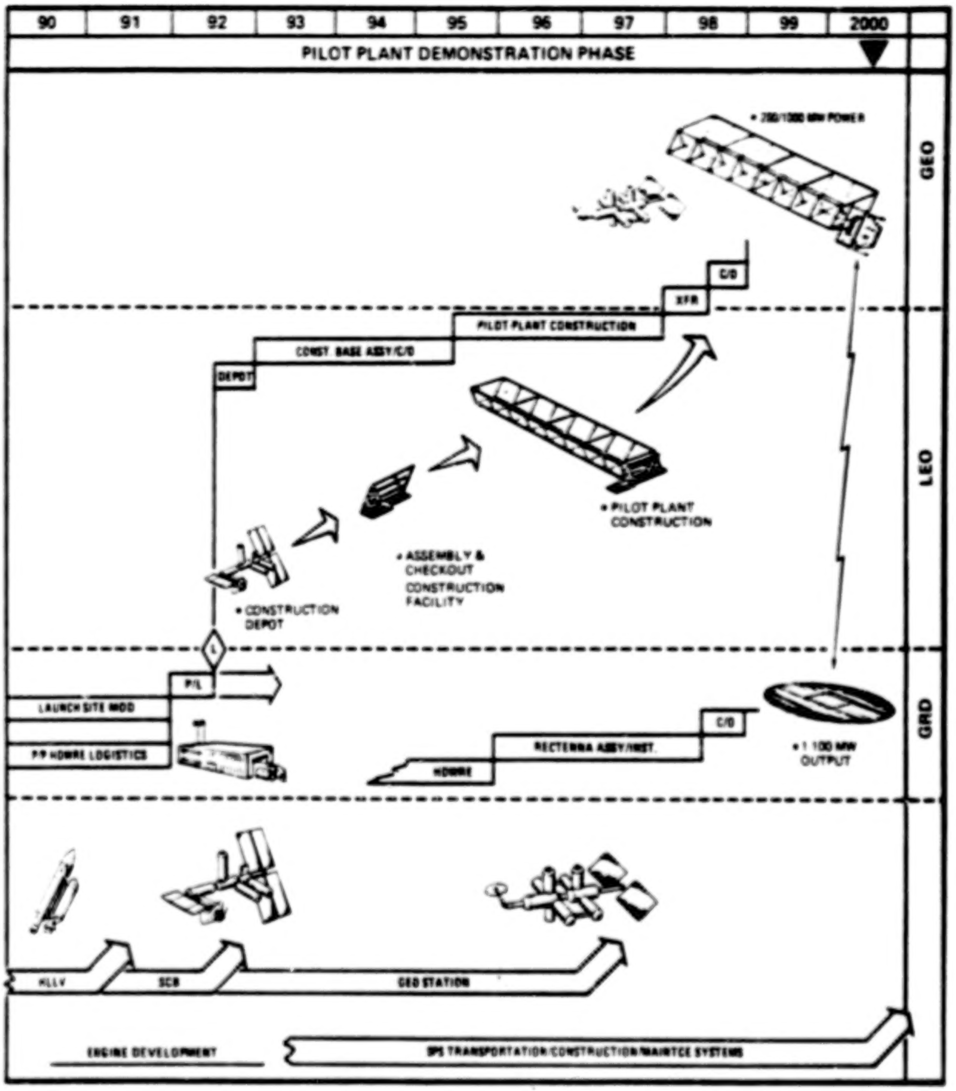

90
91
92
93
94
95
96
97
98
99
2000
PILOT PLANT DEMONSTRATION PHASE
GEO
LEO
GRD
• 200/1000 MW POWER
C/O
XFR
PILOT PLANT CONSTRUCTION
CONST. BASE ASSY/C/O
DEPOT
• PILOT PLANT CONSTRUCTION
• ASSEMBLY & CHECKOUT CONSTRUCTION FACILITY
• CONSTRUCTION DEPOT
L
P/L
LAUNCH SITE MOD
P/P HDWRE LOGISTICS
HDWRE
RECTENNA ASSY/INST.
C/O
• 1 100 MW OUTPUT
HLLV
SCB
GEO STATION
ENGINE DEVELOPMENT
SPS TRANSPORTATION/CONSTRUCTION/MAINTCE SYSTEMS

*Figure 3.0-1. SPS Pilot Plant Demonstration Phase*

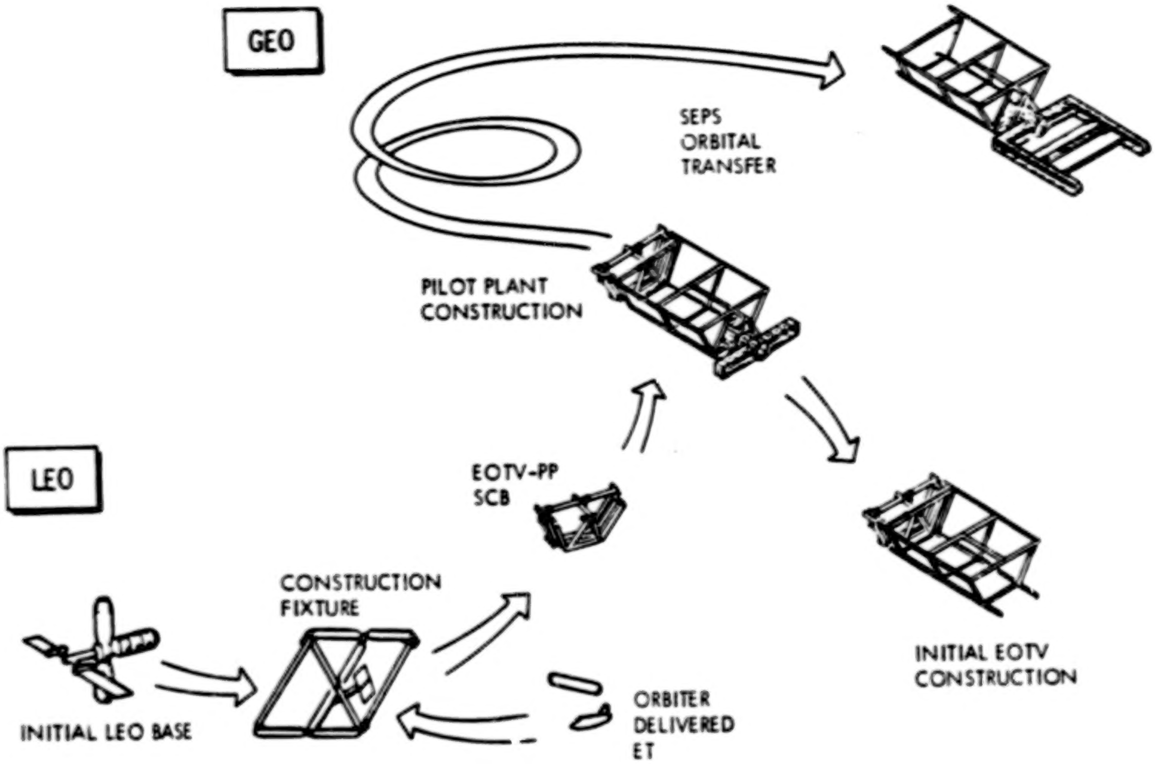

GEO
SEPS
ORBITAL
TRANSFER
PILOT PLANT
CONSTRUCTION
LEO
EOTV-PP
SCB
CONSTRUCTION
FIXTURE
INITIAL EOTV
CONSTRUCTION
ORBITER
DELIVERED
ET
INITIAL LEO BASE

*Figure 3.1-1. EOTV-Pilot Plant Construction Scenario*

SPS go-ahead, the remainder of the SCB would be completed, initial EOTV's constructed, and the SCB transferred to GEO, using one or more EOTV's for propulsion and attitude control.

The pilot plant demonstrator would be sized to the projected EOTV power level of 335 MW at the array. Allowing for radiation degradation and power distribution losses, power to the microwave antenna would be approximately 285 MW. Microwave transmission losses would reduce this value to about 230 MW at the rectenna. This would result in recovery of 8 MW of power for a 7-km-diameter rectenna or 2 MW of power for a 1.75-km-rectenna.

## 3.2 SCB CONSTRUCTION SEQUENCE

One of the most critical concerns in the EOTV-pilot plant construction scenario (and in the SPS concept) is the constructability of the SCB itself, its short dimension being more than an order of magnitude greater than cargo dimensions of currently projected earth launch vehicles. The largest, presently programmed, potentially useful structural elements deliverable to LEO are the shuttle external tanks (ET's). The pilot plant construction scenario reflects the utilization of expended ET's in constructing the construction fixtures which will be used to construct the major beam elements of the SCB. Approximately 22 of these ET's will be required, and could be obtained by boosting expended tanks into a common orbit after orbiter separation rather than directing them back to earth as now planned. The operational concept consists of assembling the 16 ET's into fixtures (Figure 3.2-1). Two of the fixtures (mirror images of each other) configured as shown in Figure 3.2-2, require 8 ET's each. A third fixture, assembled from 6 ET's, is shown as the 50 m tribeam fabrication facility in Figure 3.2-3. The attach fittings, collapsible connecting members, and beam machines are fabricated on earth and carried to LEO via the shuttle. When assembled, two of the fixtures equipped with nine 2 meter beam machines each as indicated in Figure 3.2-2, are utilized to construct the diamond shape SCB fabrication facility structural base. The third fixture is equipped with 6 beam machines and provides the jig for construction tribeam fabricators and interface fittings which are elements of the SCB. The fabrication facility is then used to generate and assemble the SCB structure, the SCB being fabricated from beams of the same section properties as the fabrication facility.

Concurrent with assembly of the work fixtures, or jigs, it is necessary to incorporate provisions for crews, electrical power, and attitude control. This is accomplished by the use of specialized modules which are compatible with shuttle payload capabilities and which can be assembled in orbit to any size complex, dependent on requirements. Figure 3.2-2 shows a power module which provides sufficient electrical power for crew life support equipment and for operating the construction equipment.

## 3.3 PILOT PLANT CONSTRUCTION SEQUENCE

A portion of the construction sequence for the pilot plant vehicle, utilizing the SCB described in Section 3.2 is illustrated serially in Figures 3.3-1 through 3.3-4.

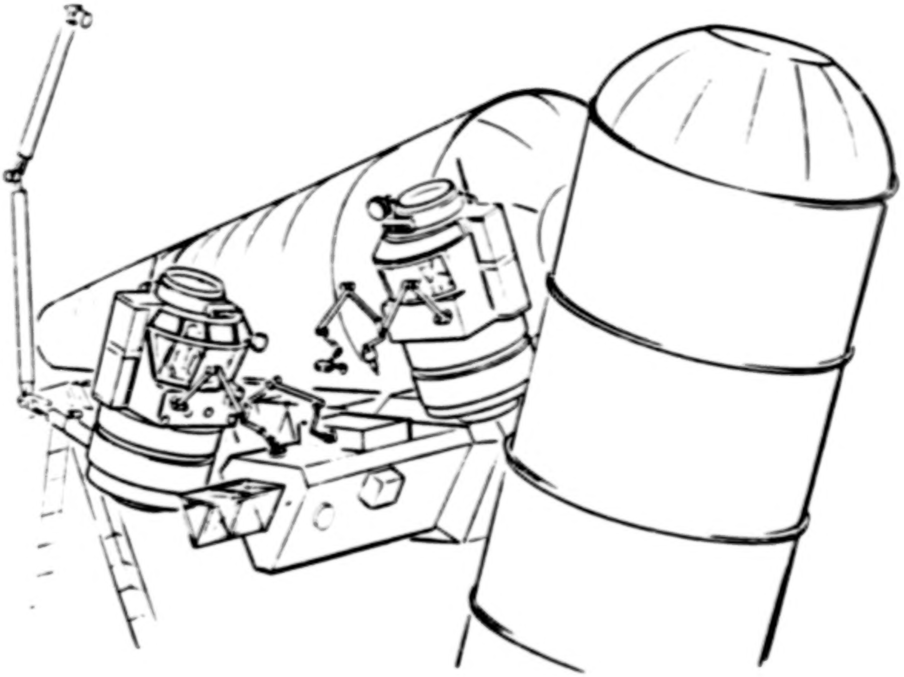


*Figure 3.2-1. ET Facility Buildup*

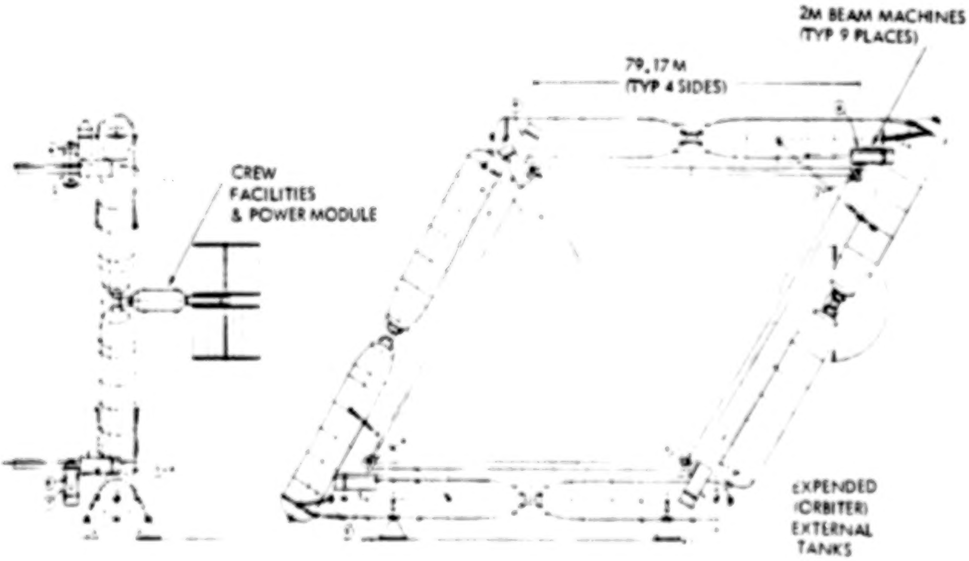

2M BEAM MACHINES
(TYP 9 PLACES)
79.17 M
(TYP 4 SIDES)
CREW
FACILITIES
& POWER MODULE
EXPENDED
(ORBITER)
EXTERNAL
TANKS

*Figure 3.2-2. Mobile 79m Girder Fabrication Facility (Right-Hand Shown)*

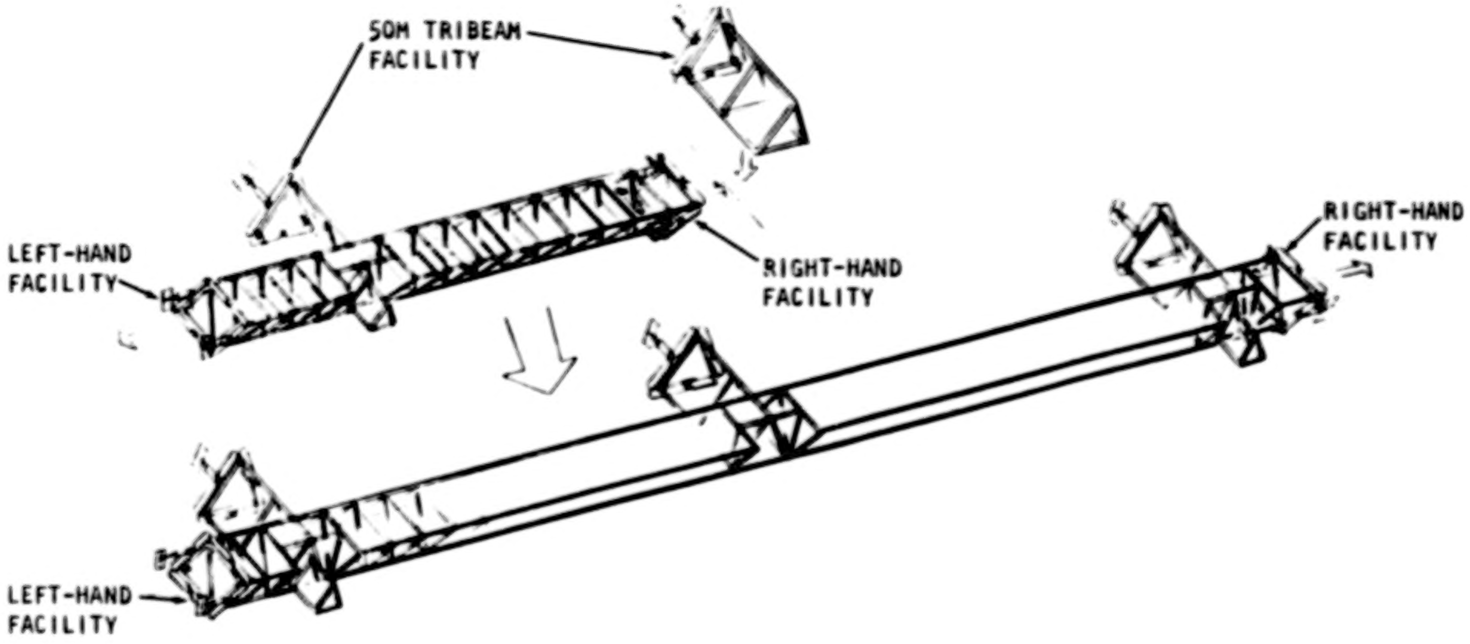

50M TRIBEAM
FACILITY
LEFT-HAND
FACILITY
RIGHT-HAND
FACILITY
RIGHT-HAND
FACILITY
LEFT-HAND
FACILITY

*Figure 3.2-3. Assembly Concept SCB/EOTV Fabrication Facility*

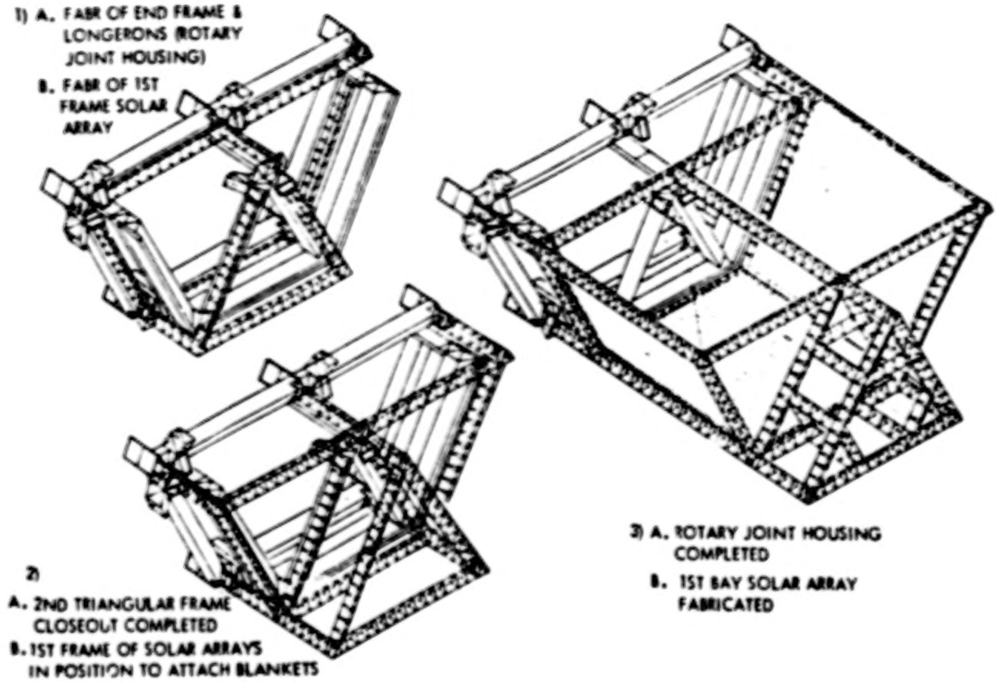

1) A. FABR OF END FRAME & LONGERONS (ROTARY JOINT HOUSING)
B. FABR OF 1ST FRAME SOLAR ARRAY
2) A. 2ND TRIANGULAR FRAME CLOSEOUT COMPLETED
B. 1ST FRAME OF SOLAR ARRAYS IN POSITION TO ATTACH BLANKETS
3) A. ROTARY JOINT HOUSING COMPLETED
B. 1ST BAY SOLAR ARRAY FABRICATED

*Figure 3.3-1. EOTV/DEMO SPS Construction Sequence Slipring/Rotary Joint Housing Structure*

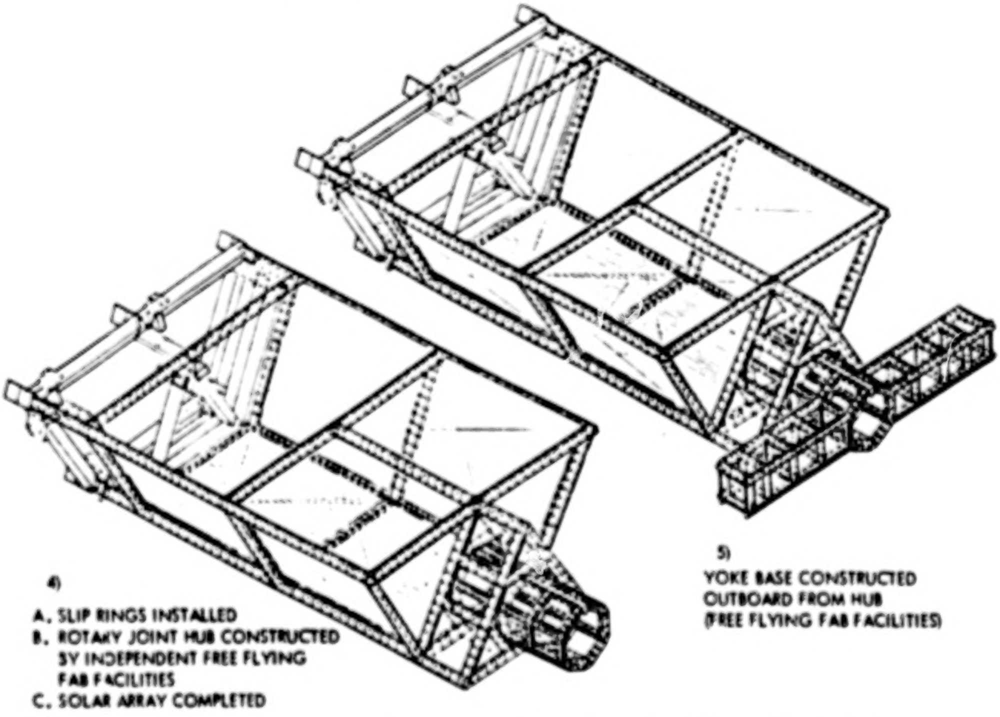
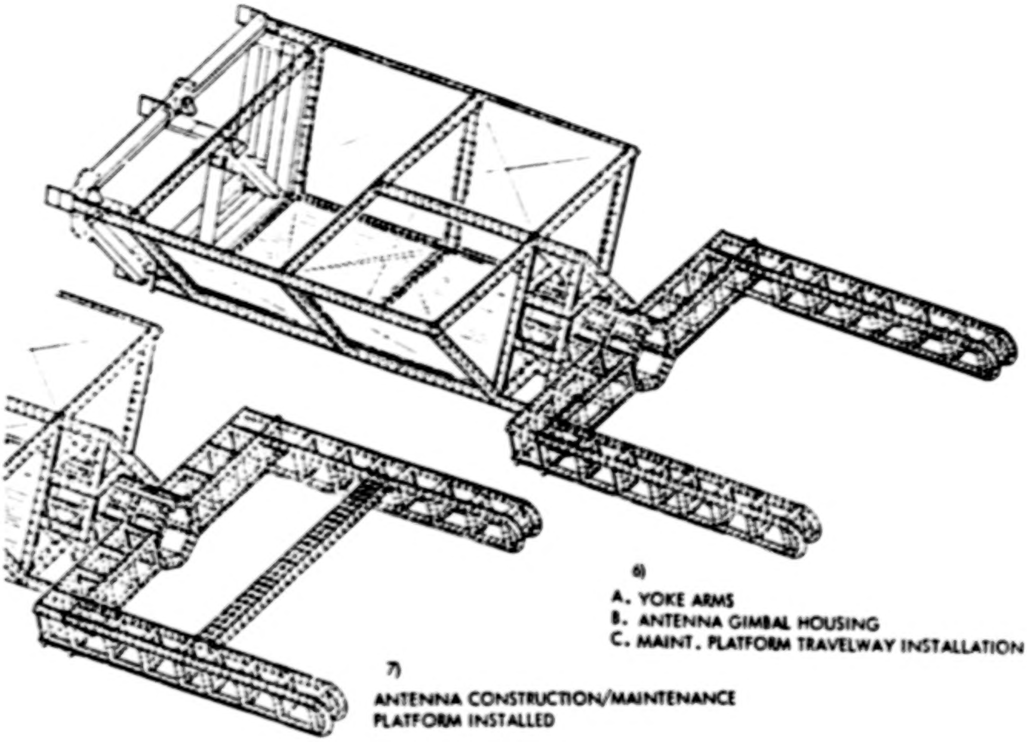

4) A. SLIP RINGS INSTALLED
B. ROTARY JOINT HUB CONSTRUCTED BY INDEPENDENT FREE FLYING FAB FACILITIES
C. SOLAR ARRAY COMPLETED
5) YOKE BASE CONSTRUCTED OUTBOARD FROM HUB (FREE FLYING FAB FACILITIES)

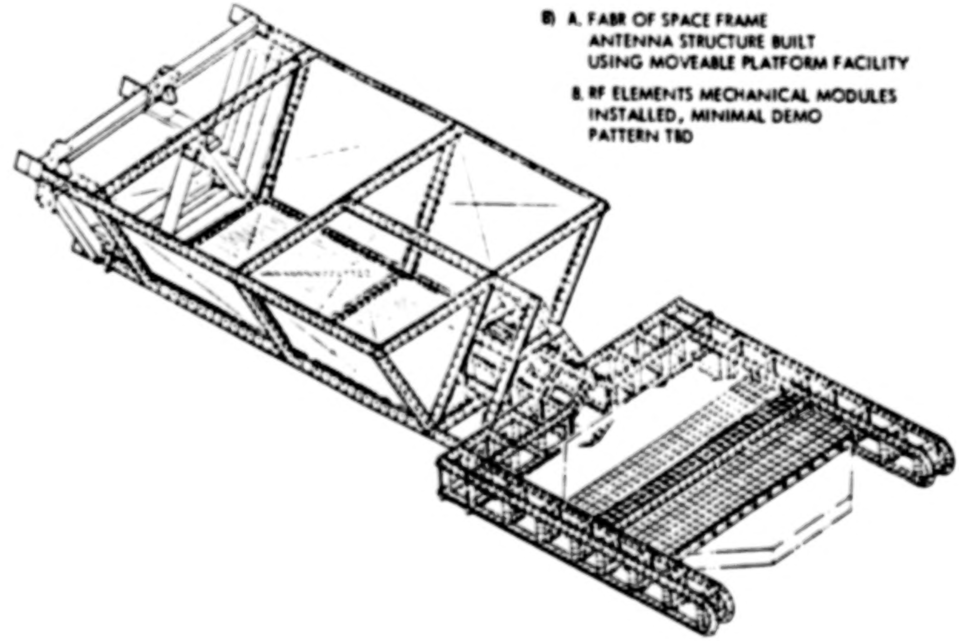
*Figure 3.3-2. EOTV/DEMO SPS Construction Sequence Slipring, Rotary Hub & Yoke Base*



6)
A. YOKE ARMS
B. ANTENNA GIMBAL HOUSING
C. MAINT. PLATFORM TRAVELWAY INSTALLATION

7)
ANTENNA CONSTRUCTION/MAINTENANCE
PLATFORM INSTALLED

Figure 3.3-3. EOTV/DEMO SPS Construction Sequence
Yoke Arms & Antenna Fab/Maint. Platform



8) A. FABR OF SPACE FRAME
ANTENNA STRUCTURE BUILT
USING MOVEABLE PLATFORM FACILITY

B. RF ELEMENTS MECHANICAL MODULES
INSTALLED, MINIMAL DEMO
PATTERN TBD

Figure 3.3-4. EOTV/DEMO SPS Construction Sequence
Space Frame Antenna

# 4.0 SUPPORTING RESEARCH AND TECHNOLOGY

This section presents, in summary form, those early analysis/experimental research tasks required to provide the requisite proof of feasibility for critical issue technology elements of the SPS system. Establishment of firm designs, performance levels, development requirements, cost/efficiency trades, and system environmental acceptability all depend on early verification of the achievable characteristics of many critical subsystem components/elements.

The proposed supporting research and technology (SRT) tasks in this section are grouped by major subsystem technologies as listed below.

- Microwave Power Transmission Technology
- Power Conversion Technology
- Power Distribution Technology
- Structures Technology
- STS Propulsion Technology

Individual tasks within each subsystem technology area are presented in RTOP format including justification, objectives, approach, task schedules, and costs.

These proposed tasks reflect SPS concept definition design decisions at this point in time, and cannot be considered as all-inclusive. Subsequent point-design decisions and guidelines will dictate continuing reassessment and updating of this preliminary SPS SRT task plan.

# SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

● **TECHNOLOGY TITLE** MICROWAVE POWER TRANSMISSION TECHNOLOGY

## ● TECHNICAL SUMMARY

The objective of this effort is to conduct critical early analyses and exploratory technology relating to microwave energy transmission key technical issue resolution and fundamental technical feasibility. The tasks in this plan address critical component definition issues relative to microwave power amplification and transmission, ground power rectification, and initial definition of microwave ground test range requirements and characteristics. Computer simulation modeling, experimental lab development and engineering model evaluation will be performed.

## ● TASK SUMMARY

| | FUNDING $K | |
|---|---|---|
| TITLE | 80 | 81 |
| 1) Ground Test Range Definition | 100 | 150 |
| 2) 50 kW Klystron Definition | 200 | |
| 3) RCR Concept Evaluation | 100 | 100 |
| 4) Antenna Pattern Calculation | 100 | |
| 5) GaAs Diode Concept Evaluation | 50 | 100 |
| 6) Power Transistor Definition | 100 | |
| | 650 | 350 |

# SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** MPTS GROUND TEST RANGE DEFINITION

- **JUSTIFICATION**

A very large percentage of MPTS critical technical issues can be substantially resolved through a comprehensive, progressive microwave transmission ground development program. A more precise definition of required ground test range requirements and facilities is an essential prerequisite to initiation of MPTS subsystem development.

- **TECHNICAL OBJECTIVES**

To determine specific detailed verification test and performance requirements and test system concepts for ground to ground (near-field) and ground to geosynchronous orbit (far-field) verification testing of MPTS subsystem elements, including interface parameters and requirements for a geosat multi-function test system operating in conjunction with a 1 km ground linear array.

- **APPROACH**

Task sequence will be to establish sequential technical issue resolution requirements, define overall test system characteristics and conduct system concept definition studies for principal ground test elements. The following subtasks will be performed:

a) Define MPTS critical technology verification resolution requirements as a parametric basis for proposed test system objectives.

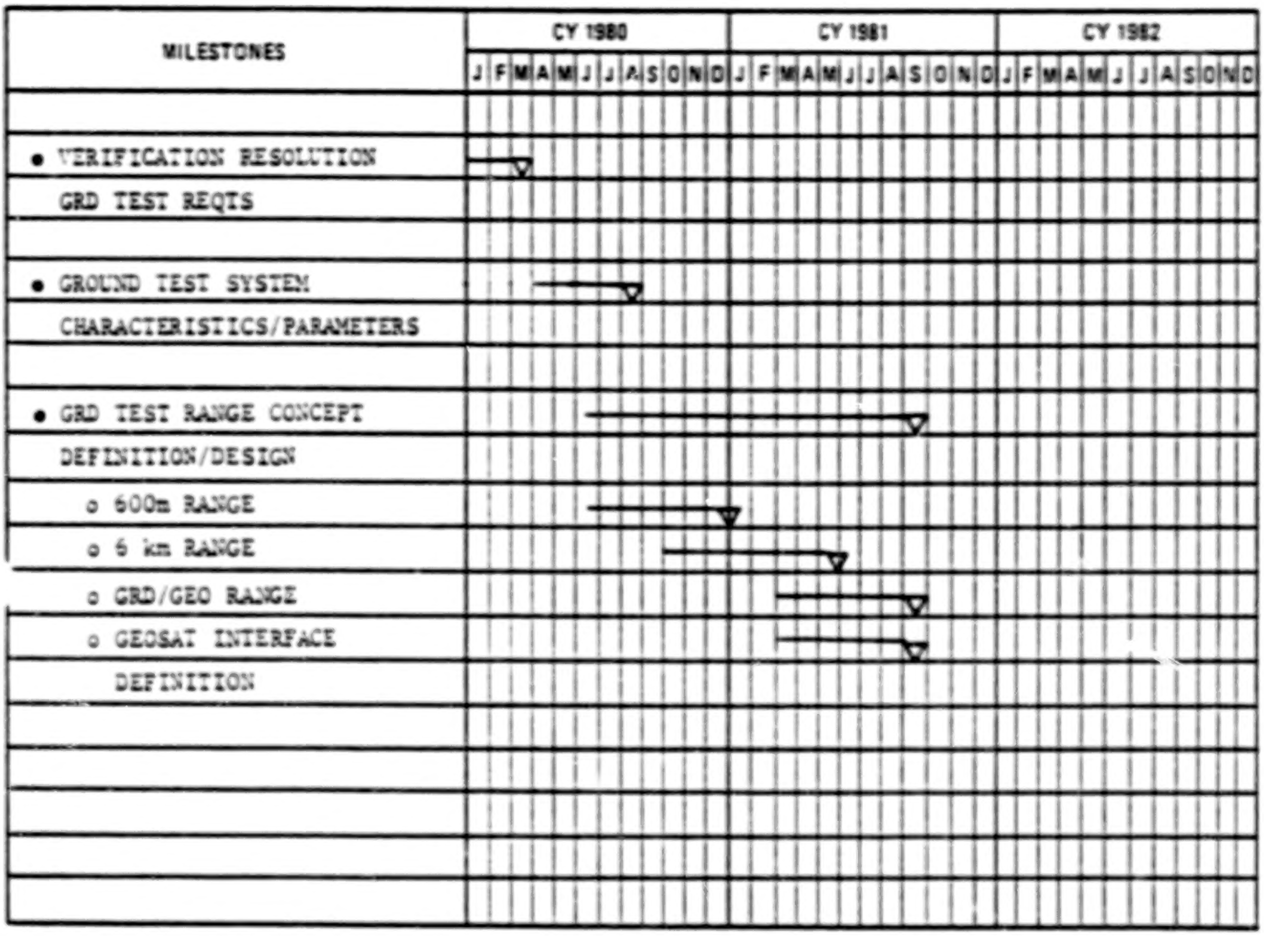
b) Describe overall sequential end-to-end MPTS system test characteristics including location, power requirements, instrumentation, etc.

c) Develop preliminary design concept definition for 600 meter and 6 km ground to ground test ranges and a ground to geo 1 km linear array antenna installation.

# SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** MPTS GROUND TEST RANGE DEFINITION

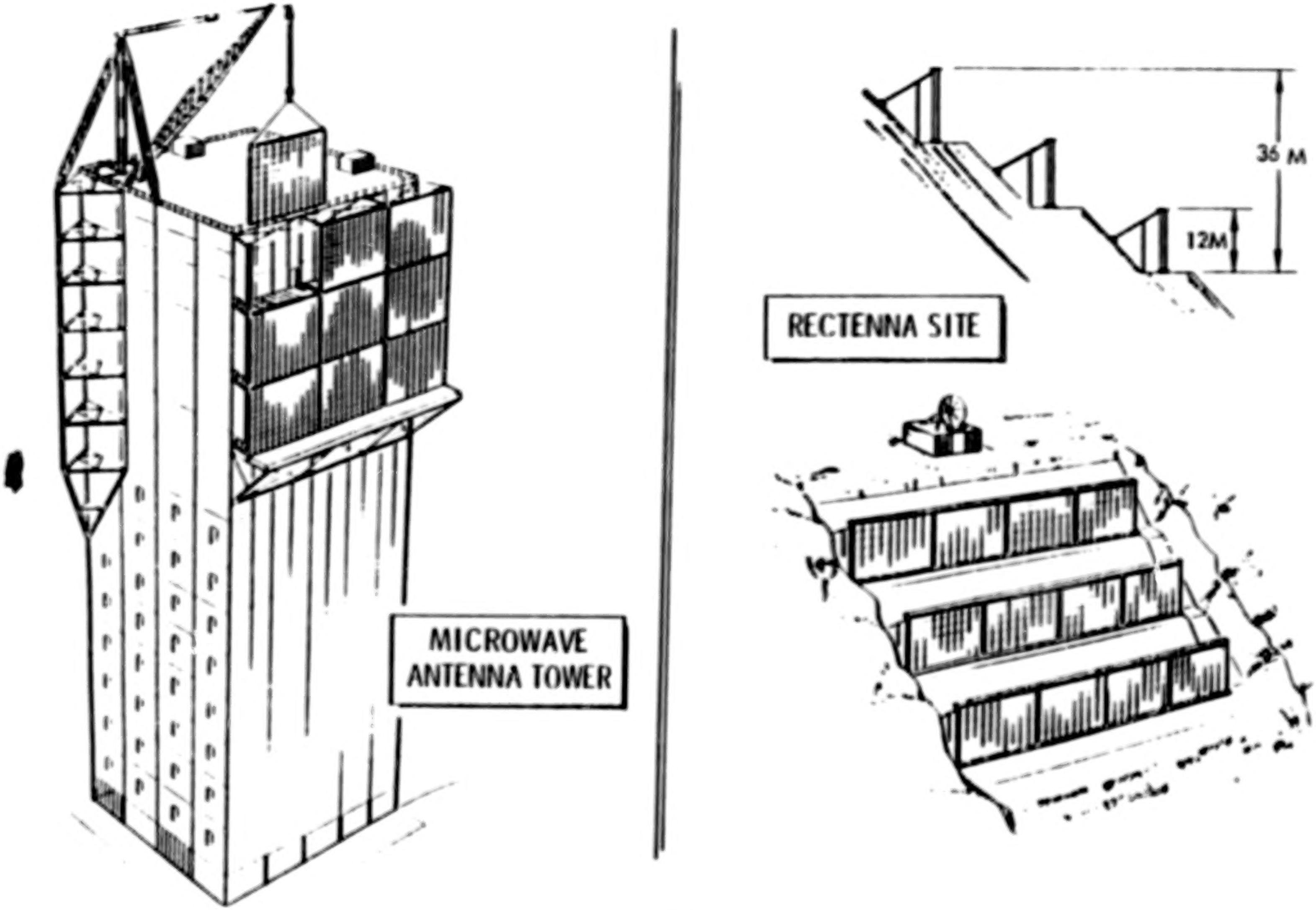
- **MILESTONE SCHEDULE**



NOTES:

| **• RESOURCE REQUIREMENTS** | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING | $100 K | $150 K | |
| • FACILITIES | | | |

4-5


MICROWAVE
ANTENNA TOWER
36 M
12M
RECTENNA SITE

GROUND-TO-GROUND NEAR-FIELD MICROWAVE TEST RANGE

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** 50 KW KLYSTRON DEFINITION

- **JUSTIFICATION**

The high-power Klystron converter must be completely characterized and defined before MPTS design definition can be initiated. Klystron electrical definition requires application of the "floppy disc" digital electron-beam simulation program. Collector electron optics requires analogue simulation.

- **TECHNICAL OBJECTIVES**

Perform computational simulation in a computer-aided-design process to define an optimized SPS Klystron, generate initial design and assembly sequences and provide a basis for cost and performance prediction.

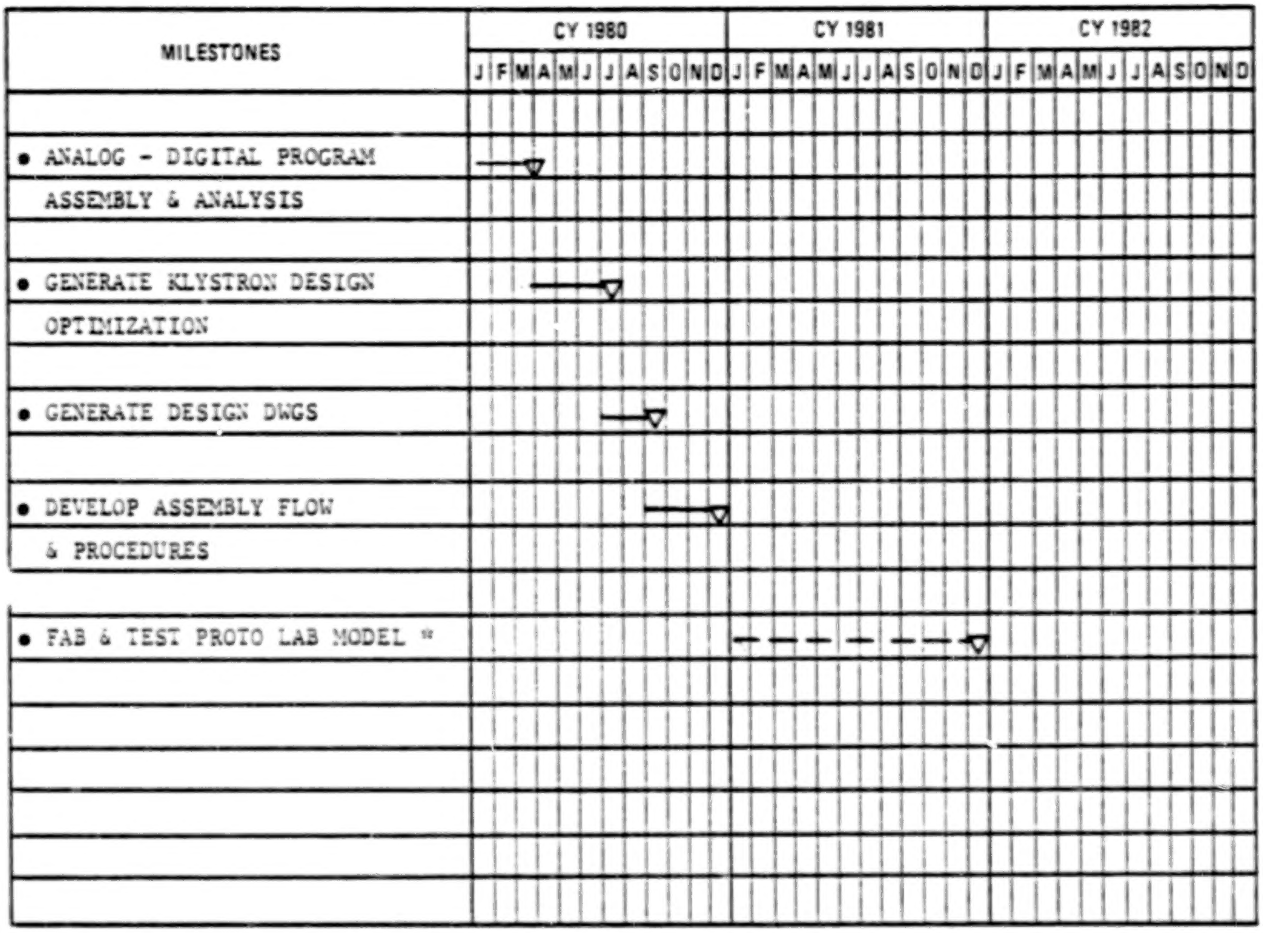
- **APPROACH**

1. Assemble and proof analogue and digital programs
2. Perform Klystron definition simulation optimization
3. Generate design drawings
4. Develop assembly flow scenario and instructions

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** 50 KW KLYSTRON DEFINITION

- **MILESTONE SCHEDULE**



NOTES:

*Proto Klystron lab model fab & test projected as Component Development Task

| ● RESOURCE REQUIREMENTS | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| ● FUNDING | $200 K | - | - |
| ● FACILITIES | TBD | | |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** RCR CONCEPT EVALUATION

- **JUSTIFICATION**

An integrated microwave - radiator/power converter module must be characterized and developed in detail as a necessary prerequisite to point-design MPTS performance, mass and cost determinations.

- **TECHNICAL OBJECTIVES**

Perform development of a point-design RCR/Klystron module with required pattern, adequate cooling and an economical manufacturing process. Ohmic cost will be considered a major parameter.

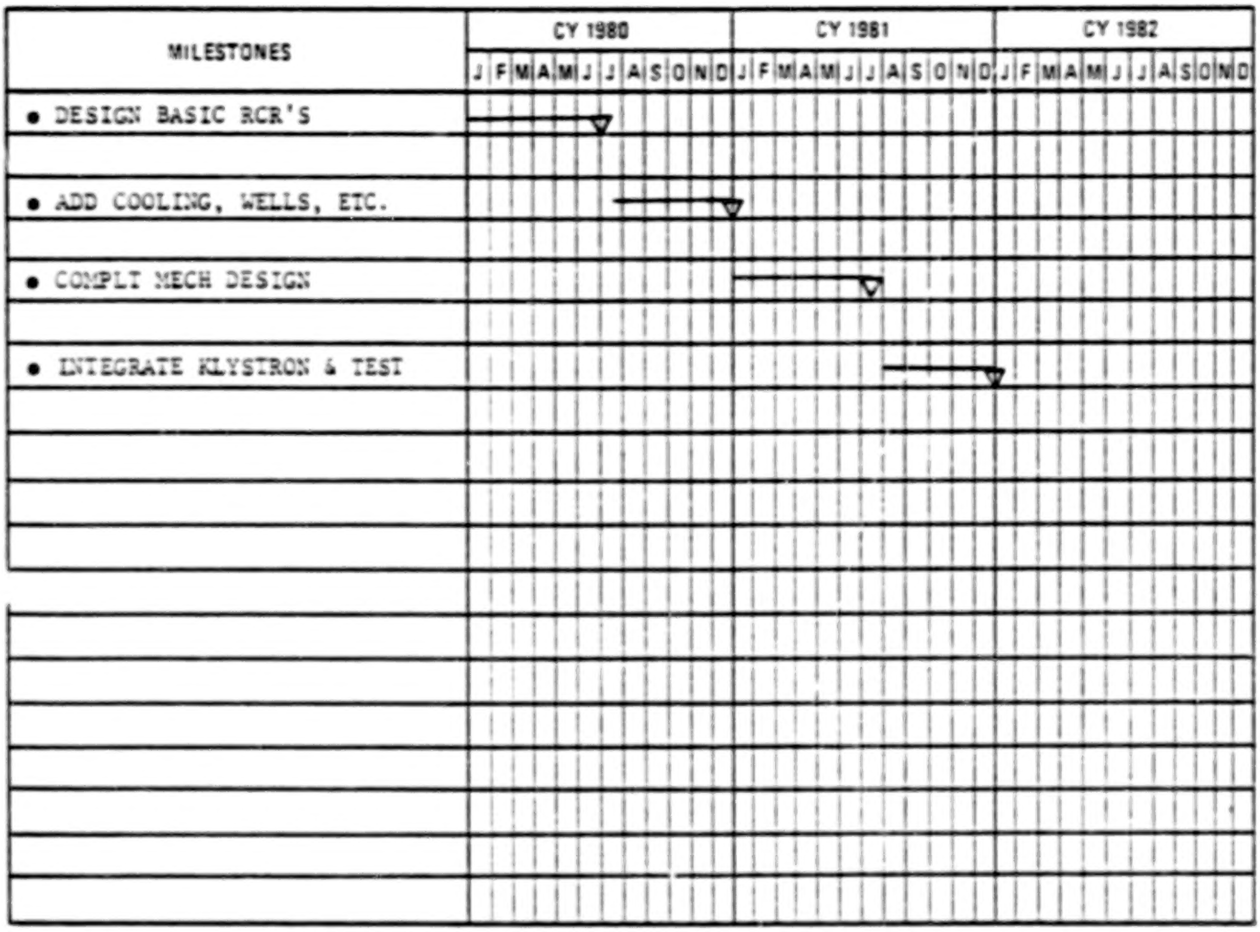
- **APPROACH**

Resonant Cavity Resonator configurations of various characteristics will be designed and evaluated. Variants will include feeder placement, introduction of the klystron well, addition of heat-pipe grid, and use of choke joints for assembly. Experimental model will be tested in a space simulator for cooling performance, multipaction, temperature distribution and other performance characteristics.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** RCR CONCEPT EVALUATION

- **MILESTONE SCHEDULE**



NOTES:

- **RESOURCE REQUIREMENTS**

| | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING | $100 K | $100 K | |
| • FACILITIES | | YES | |

# SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** MPTS ANTENNA PATTERN CALCULATION

- **JUSTIFICATION**

Microwave beam computed patterns taking into account all deviations from ideal behavior are required for projected point-design MPTS antenna concepts prior to developmental hardware testing. Later ground to geo line array pattern measurements must correlate well with antenna pattern modeling to verify antenna design adequacy.

- **TECHNICAL OBJECTIVES**

Assemble a specialized computer program for calculation of MPTS antenna array and line source simulation pattern behavior.

- **APPROACH**

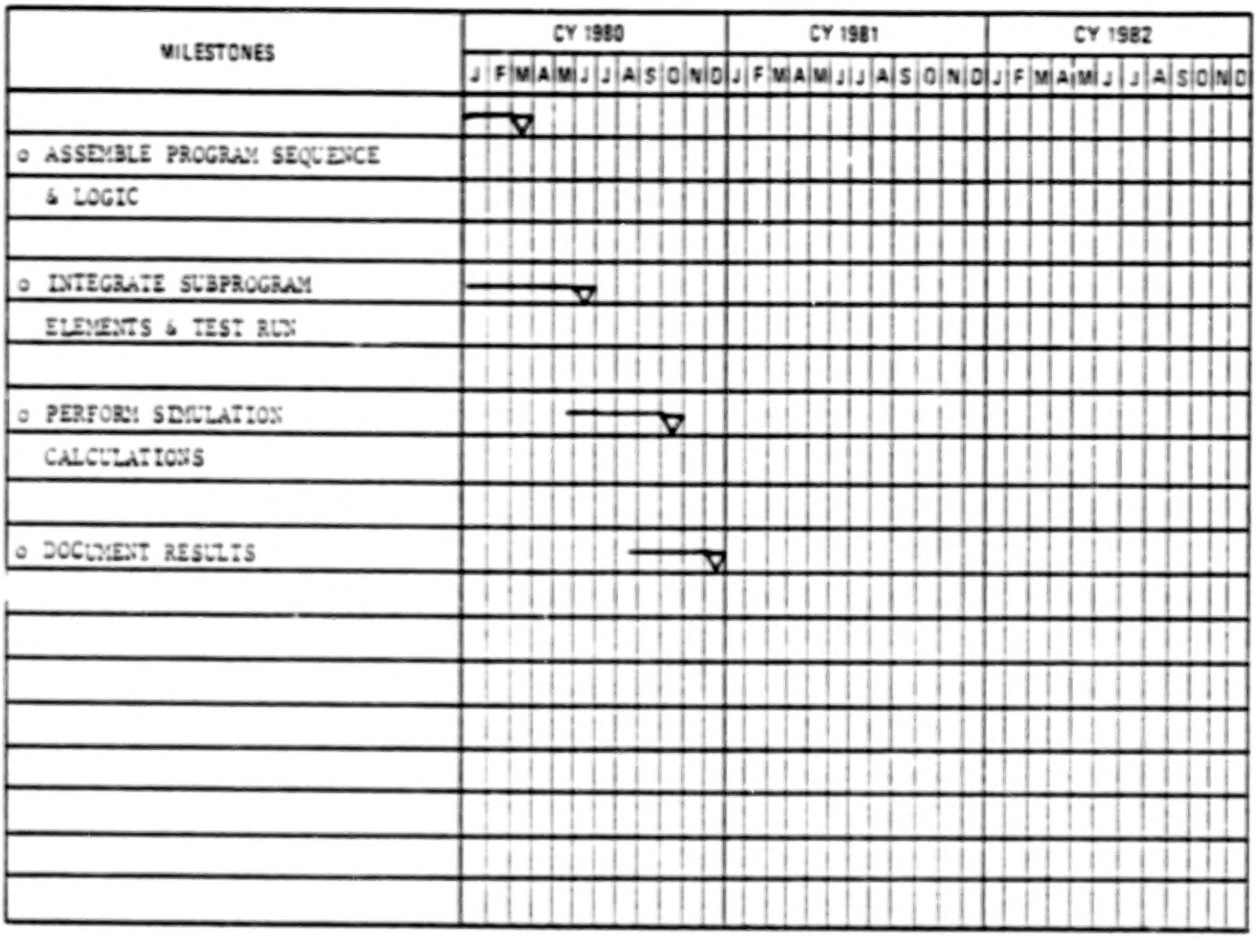
1. Construct an optimized computer program using as subprograms, existing programs for computing line and planar array patterns from the array excitation.
2. The main program will identify excitation functions by calling subprograms which generate perturbations of the ideal excitations generated in the MAINGO.
3. Evaluate and utilize the following subprograms:

    - MAINGO
    - LOCATE
    - RETRO
    - STEER
    - WEIGHT
    - XFORM1
    - XFORM2
    - VALUES
    - RECTNA
    - PRTPLT
    - CRTPLT
    - TBLPLT

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** MPTS ANTENNA PATTERN CALCULATION

- **MILESTONE SCHEDULE**



NOTES:

- **RESOURCE REQUIREMENTS**

| | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING | $100 K | | |
| • FACILITIES | (COMPUTATION) | | |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** GaAs DIODE CONCEPT EVALUATION

- **JUSTIFICATION**

Diode and corollary rectifier circuits must be characterized and developed as a prerequisite to SPS rectenna configuration definition and cost and performance determination.

- **TECHNICAL OBJECTIVES**

Develop diode and rectifier circuit software programs, evolve optimum diode and circuit design and evolve efficient fabrication processes. Inasmuch as problems in defining GaAs parameters are the same as for the GaAs transistor program task, perform this task in parallel.

- **APPROACH**

The development of the diode CAD program can be a simplification of the Waterloo transistor program, BIPOLE. As in the transistor case either WATAND or REPAC can be used for the CAD rectifier circuit program. Test diodes are then made and compared with the computer program results. GaAs parameters and structure data is modified according to lab results then new designs are run. This will continue until an optimum design is obtained.

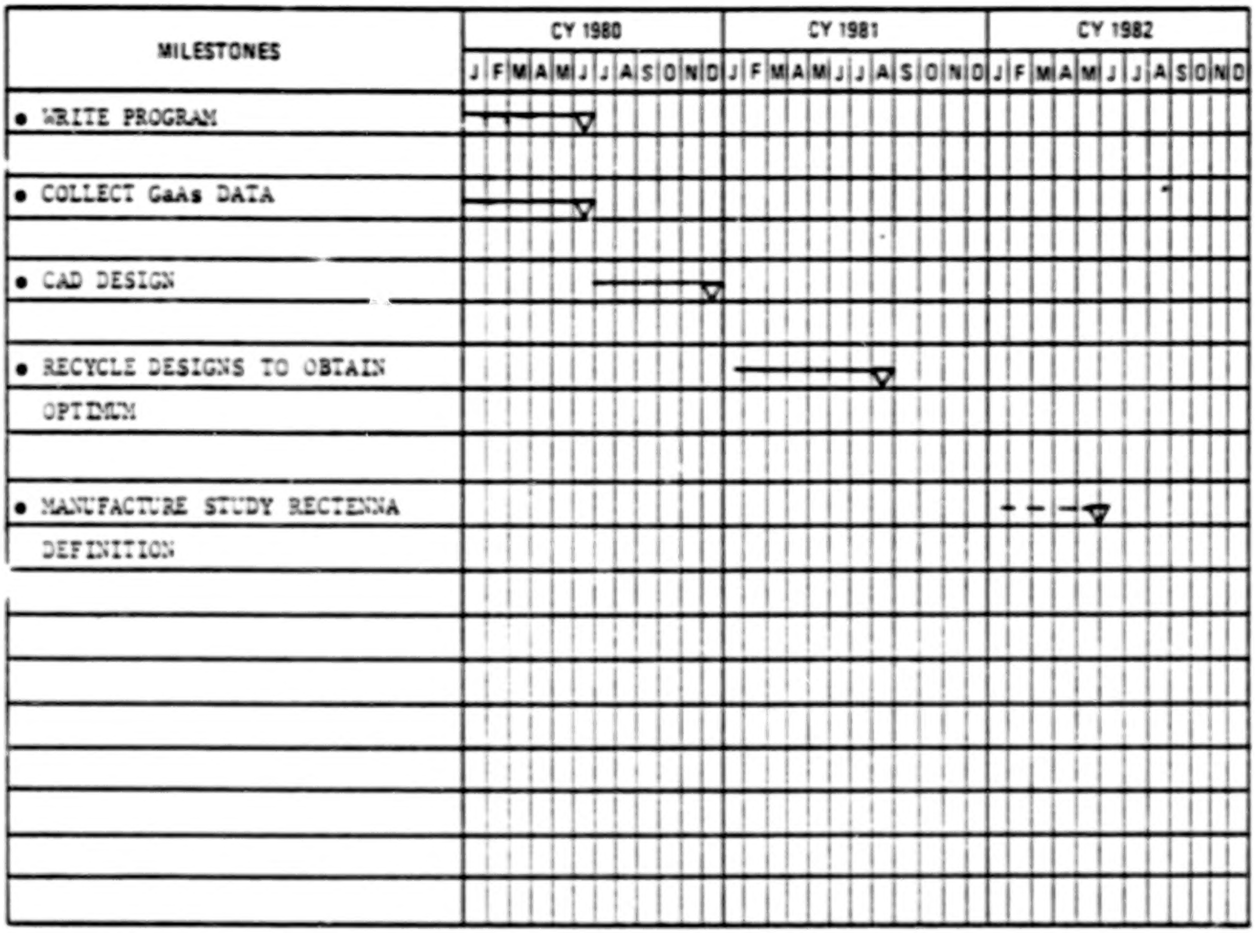
Rectenna performance will then be calculated in light of the optimum design parameters.

Finally large-scale manufacture methods will be projected from the laboratory fab processes and volume production costs estimated.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** GaAs DIODE CONCEPT EVALUATION

- **MILESTONE SCHEDULE**



- WRITE PROGRAM
- COLLECT GaAs DATA
- CAD DESIGN
- RECYCLE DESIGNS TO OBTAIN OPTIMUM
- MANUFACTURE STUDY RECTENNA DEFINITION

NOTES:

| RESOURCE REQUIREMENTS | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| FUNDING | $50 K | $100 K | |
| FACILITIES | (COMPUTATION) | | |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** POWER TRANSISTOR PRELIMINARY DEFINITION

### JUSTIFICATION

A preliminary concept definition and performance evaluation of three transistor power converters must be performed as a basis for the power module point design decision by 1981 prior to component development and verification.

### TECHNICAL OBJECTIVES

Evaluate the performance and S-O-A manufacturing potential for advanced power transistor development for application to MPTS power amplification.

### APPROACH

Task will consist of an iterative process of data acquisition on GaAs parameters, calculation of optimized transistor performance and evaluation of production potential.

The task sequence includes the following:

a) Collection of preliminary GaAs parametric data

b) CAD design of transistor using variation of Waterloo program - BIPOLE

c) CAD design of amplifier circuits using either Waterloo - WATAND or RI - REPAC

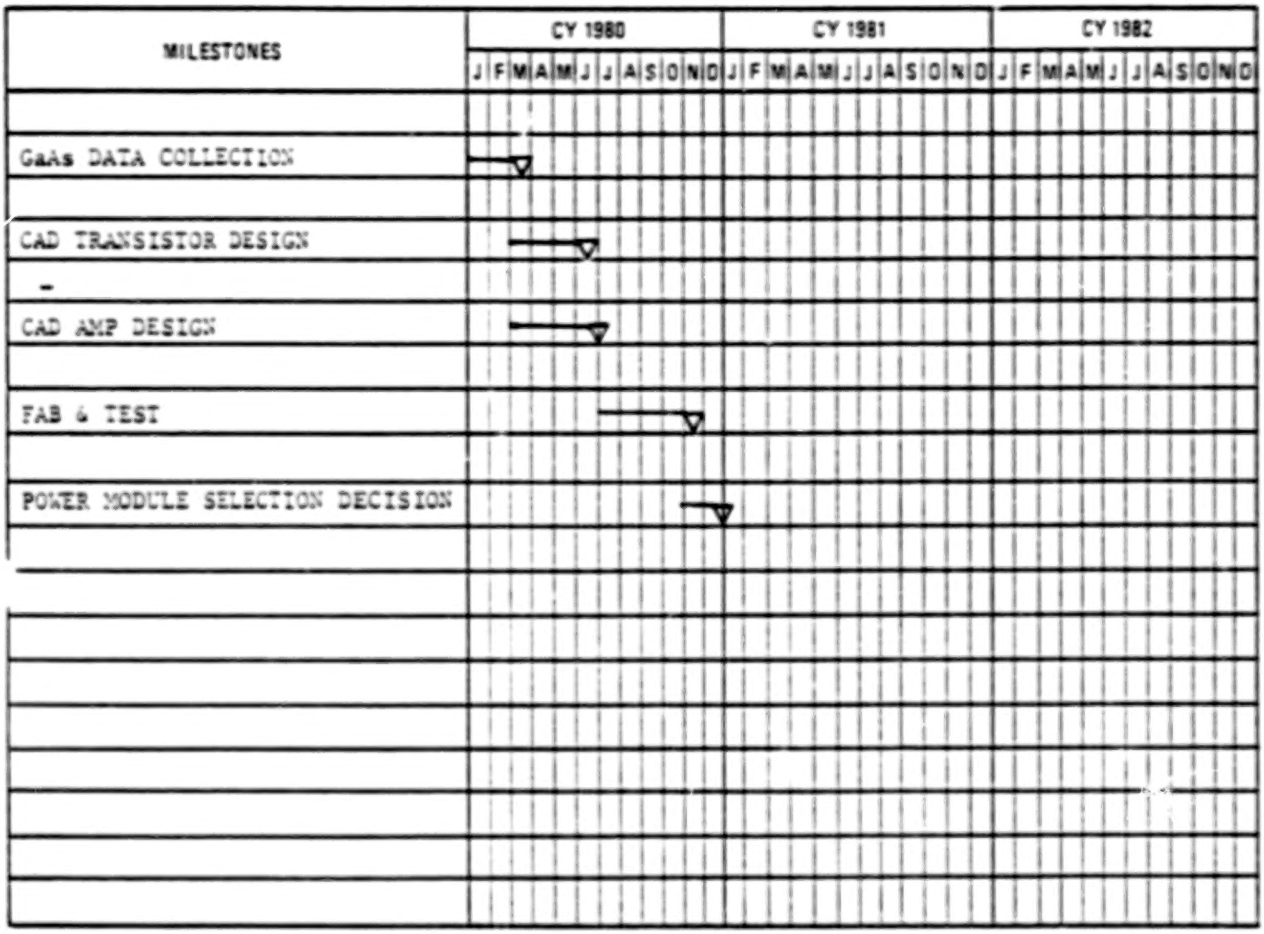
d) Fabrication and test evaluation of transistor and amplifier performance

e) Refinement of GaAs data and efficiency projection

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** POWER TRANSISTOR PRELIMINARY DEFINITION

- **MILESTONE SCHEDULE**



NOTES:

- **RESOURCE REQUIREMENTS**

| | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING | $100 K | | |
| • FACILITIES | | | |

● TECHNOLOGY TITLE SPS POWER CONVERSION TECHNOLOGY

● TECHNICAL SUMMARY

The objective of this program is to identify and develop the component and subsystem technologies for an advanced photovoltaic conversion subsystem to support the SPS design and trade off studies. The GaAlAs photovoltaic subsystem has the potential of low weight, increased performance, higher resistance to ionized radiation levels and the ability to operate with concentrators with minimum loss in performance compared to Si cells and it should actively be developed. Determination of the state-of-the-art, analyses, computer modeling, design and trade off studies, and fabrication, test and development of the major components will be conducted in the proposed program.

● TASK SUMMARY

1. GaAs Solar Cell Advanced Development - The objective of this program is to develop a GaAs cell for space applications with a minimum efficiency of 20% at AMO and 28°C. The development of a 20% GaAs cell is required for a practical design of a Solar Power Satellite for the post 1995 time period. High efficiency, high production capabilities associated with low cost is required. The following are required to develop the GaAs solar cell: Investigation of cell structures, cell fabrication and characterization, radiation/annealing evaluations, material development and improvements and manufacturing processes.
2. CVD Fabrication Process Scale-up - The objective of this program is to continue and improve the CVD fabrication process in order to obtain increased yields and high efficiency GaAs cells. To support the SPS solar cell design it is necessary to perform research and development to establish the technology base for the required cell materials, interconnect mechanisms, mounting and bonding processes, contact methods, continuous flow processing and in line monitoring (layer thickness, doping concentration, junction integrity, diode characteristics, contact resistance, photovoltaic response, AR coatings).
3. Solar Cell & Reflector Radiation Tests - The objective of this program is to characterize the advanced GaAlAs cells and reflectors for an on orbit 30 year radiation environment. Various cell designs and reflector membrane specimens will be fabricated and tested to various radiation energy levels and fluxes in laboratory test chambers. The test results will be analyzed and used to project the component performance for the SPS mission.
4. Reflector Performance Tests - The objective of this program is to survey the industry and perform tests for determining the surface and optical properties of reflective membranes of 12.5 μm (0.5 mil) or less in thickness. Concentration ratios of approximately 7 to 8 can be used with GaAlAs cells before an active thermal control system would be required. With the higher concentration ratio the design complexity increases and the SPS sizing then becomes very sensitive to misorientation angles with respect to the sun. Preliminary analysis have indicated that concentration ratios of approximately 2 to 5 are attractive for the SPS for a passive cooled solar array design.
5. High Voltage (40 kV) Solar Cell String Design - High voltages of 40 kV to 50 kV are essential for the reduction of power distribution weight and to minimize the power distribution losses on the SPS. The high voltage arrays also permits the direct coupling of the power conversion subsystem to the microwave antenna. This eliminates the necessity of high weight power conditioning equipment to step up the array voltages to be compatible with the 40 kV klystron input.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** GaAs SOLAR CELL ADVANCE DEVELOPMENT

- **JUSTIFICATION** A solar power satellite capable of delivering 5 GW of power to the utility on the ground will require an array output of approximately 9.76 GW at the end of life. Utilizing the GaAs type cell will result in a solar blanket area of approximately 30.6 $km^2$ which is considerably less area than if Si type cells were used. The GaAs cell offers the potential of high efficiency, low weight, reduced deployment area, high efficiency at elevated operating temperatures which permits concentrators to be used for obtaining concentration ratios up to 5 to 7, and the GaAs cell is more resistant to the space radiation environment compared to Si cells.

- **TECHNICAL OBJECTIVES**

The objective of this effort are:

- Demonstrate and develop the technology for fabricating high efficiency GaAs solar cells
- Develop and apply rigorous analytical modeling techniques for predicting the performance of GaAs thin film cells
- Determine the tolerance of various GaAs solar cell configurations to irradiation by charged particles and feasibility of low temperature annealing to remove radiation damage
- Develop and improve feedstock materials for cell fabrication processes and cell structures
- Design preliminary manufacturing processes, equipment, and physical plant requirements for eventual SPS cell production

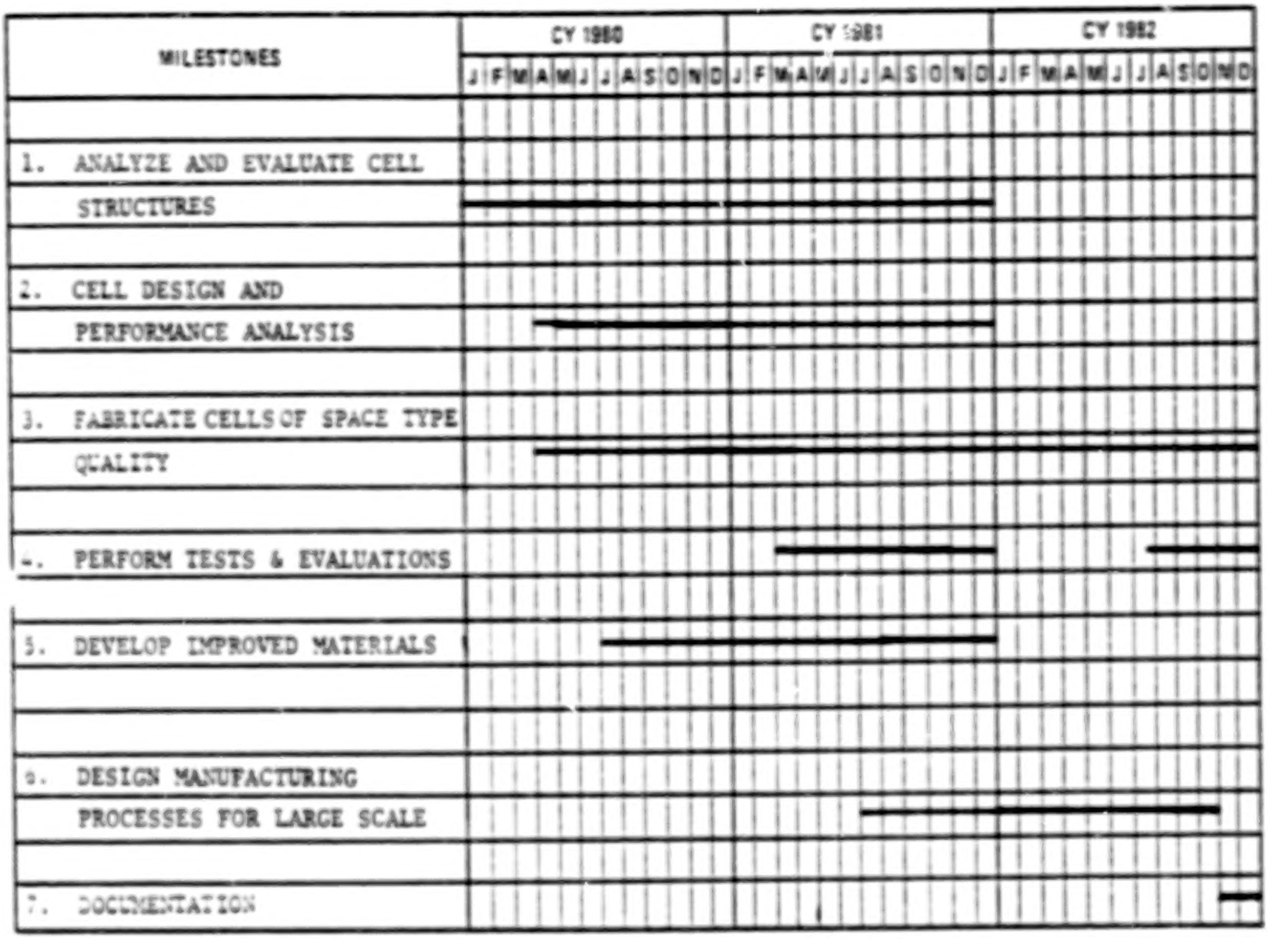
- **APPROACH**

Investigate and develop high efficiency thin film GaAs solar cell structures based on MO-CVD; model, design and performance analyzes thin film GaAs cells; determine thin film GaAs solar cell radiation damage and annealing properties; develop and improve (feedstock) materials with required properties, reduce costs and high volume production potential; and perform preliminary design and projection of manufacturing processes, production equipment, and physical plant requirements for large scale manufacture of GaAs thin film cells for SPS.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** GaAlAs CELL ADVANCE DEVELOPMENT

- **MILESTONE SCHEDULE**



NOTES.

| RESOURCE REQUIREMENTS | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| FUNDING | $900 K | $1000 K | $1500 K |
| FACILITIES | | | |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

● **TASK TITLE** CVD FABRICATION PROCESS SCALE-UP

● **JUSTIFICATION**

A solar power satellite capable of delivering 5 GW of power to the utility on the ground will require an array output of approximately 9.76 GW at the end of life. One of the major components that have a significant impact on the SPS weight and cost is the design and performance of the GaAlAs solar cell. The development and refinement of the CVD fabrication process for the manufacture of GaAlAs cells has the potential for high production rates for the cells. The CVD process has to be developed in order to obtain high performance cells with high manufacturing yields and low unit cost which are required to make the SPS economically viable with advanced power plants.

● **TECHNICAL OBJECTIVES**

Analyze the manufacturing processes and design improved techniques and equipment that will result in the manufacture of high efficiency GaAlAs cells. Fabricate and test cells to demonstrate the improved CVD processes.

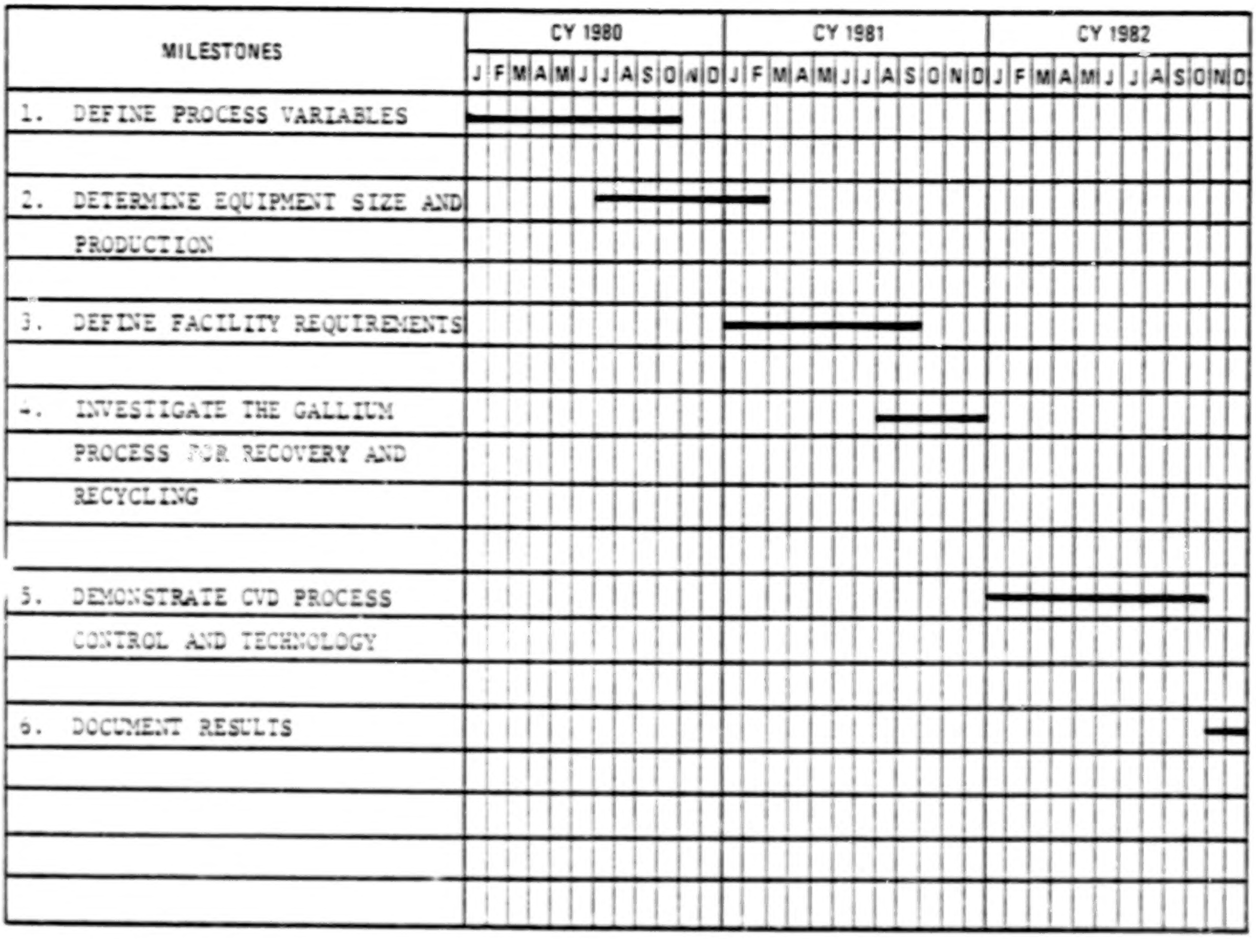
● **APPROACH**

The process variables, tolerances and the equipment size have to be defined. Establish production yields, process times, mfg costs and plant size which are necessary to determine production rates. Define facility requirements and cell costs. Analyze the gallium cycle for recycling, minimizing losses and reduction in gallium content for cell performance.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

● **TASK TITLE** CVD FABRICATION PROCESS SCALE-UP

● **MILESTONE SCHEDULE**



1. DEFINE PROCESS VARIABLES
2. DETERMINE EQUIPMENT SIZE AND PRODUCTION
3. DEFINE FACILITY REQUIREMENTS
4. INVESTIGATE THE GALLIUM PROCESS FOR RECOVERY AND RECYCLING
5. DEMONSTRATE CVD PROCESS CONTROL AND TECHNOLOGY
6. DOCUMENT RESULTS

NOTES:

| ● RESOURCE REQUIREMENTS | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| ● FUNDING | $300 K | $500 K | $800 K |
| ● FACILITIES | - | TBD | TBD |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** SOLAR CELL & REFLECTOR RADIATION TESTS

- **JUSTIFICATION** The radiation effects on solar cells and reflectors has been estimated to result in degradations of as high as 20 to 30% for the SPS type mission. The high degradation factors results in increased sizing of the SPS with additional weight and cost penalties. There is some preliminary data available that indicates these factors may be too high. A well balanced test program is required to obtain actual cell and reflector performance data for the radiation environment in order to design and determine the size and cost of the SPS with a higher confidence level.

- **TECHNICAL OBJECTIVES**

Conduct detailed analyses of the cell structure to determine methods and designs to increase the radiation resistance. Fabricate and test cells and reflective membranes to the radiation environment and correlate test data with analytically results.

- **APPROACH**

Perform analyses and computer modeling of the devices to determine the performance for the radiation environment. Conduct radiation tests on space type cells and reflector specimens and correlate and compare data with math models. Develop and evaluate techniques to minimize radiation degradation such as thermal annealing of cells, increased thickness of reflector coating, development of increased radiation harden solar cells.

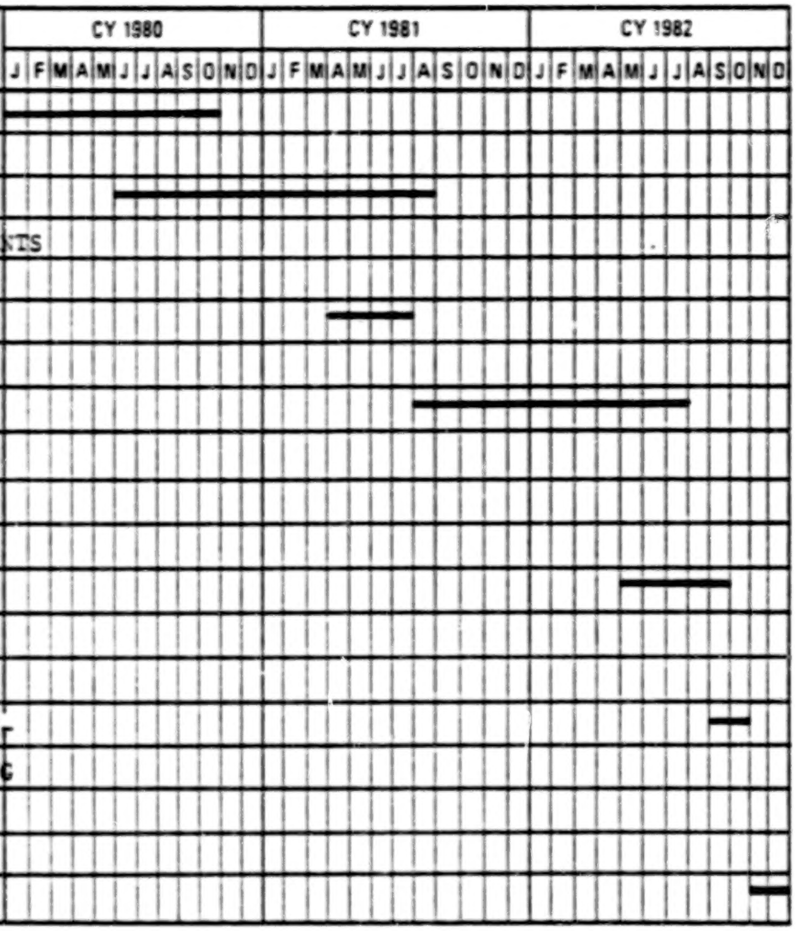
## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** SOLAR CELL & REFLECTOR RADIATION TESTS

- **MILESTONE SCHEDULE**

**MILESTONES**

1. PERFORM ANALYSES
2. WRITE COMPUTER PROGRAMS FOR RADIATION EFFECTS ON COMPONENTS
3. SELECT SAMPLES FOR TESTING
4. CONDUCT RADIATION TESTS OF FLIGHT TYPE CELL & REFLECTOR MEMBRANES
5. UPDATE AND COMPARE COMPUTER MODEL WITH TEST RESULTS
6. DETERMINE TECHNOLOGY IMPROVEMENTS FOR RADIATION HARDENING OF DEVICES
7. DOCUMENTATION



NOTES:

- RESOURCE REQUIREMENTS

| | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING | $200 K | $250 K | $300 K |
| • FACILITIES | | | |

SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- TASK TITLE REFLECTOR PERFORMANCE TESTS

- JUSTIFICATION One technique to reduce the weight and cost of a SPS photovoltaic power conversion subsystem is to employ reflective membranes to concentrate the solar energy on the cells. The reflective membranes increase the solar energy falling on the cells and therefore the high cost solar cells are partially replaced by the utilization of low weight, low cost reflective membranes. The surface reflectivity and optical properties of thin reflective membranes under tension in the space environment is practically non-existent. These design data are critical for the design of a solar concentrator photovoltaic power conversion subsystem.

- TECHNICAL OBJECTIVES

The objective of this effort is to determine the state-of-the-art of thin film reflective membranes for space missions and assess techniques for developing manufacturing methods for thinner gages and improved performance. Perform tests of the membranes to determine the surface and optical properties for use in the design of the SPS concentrator configurations.

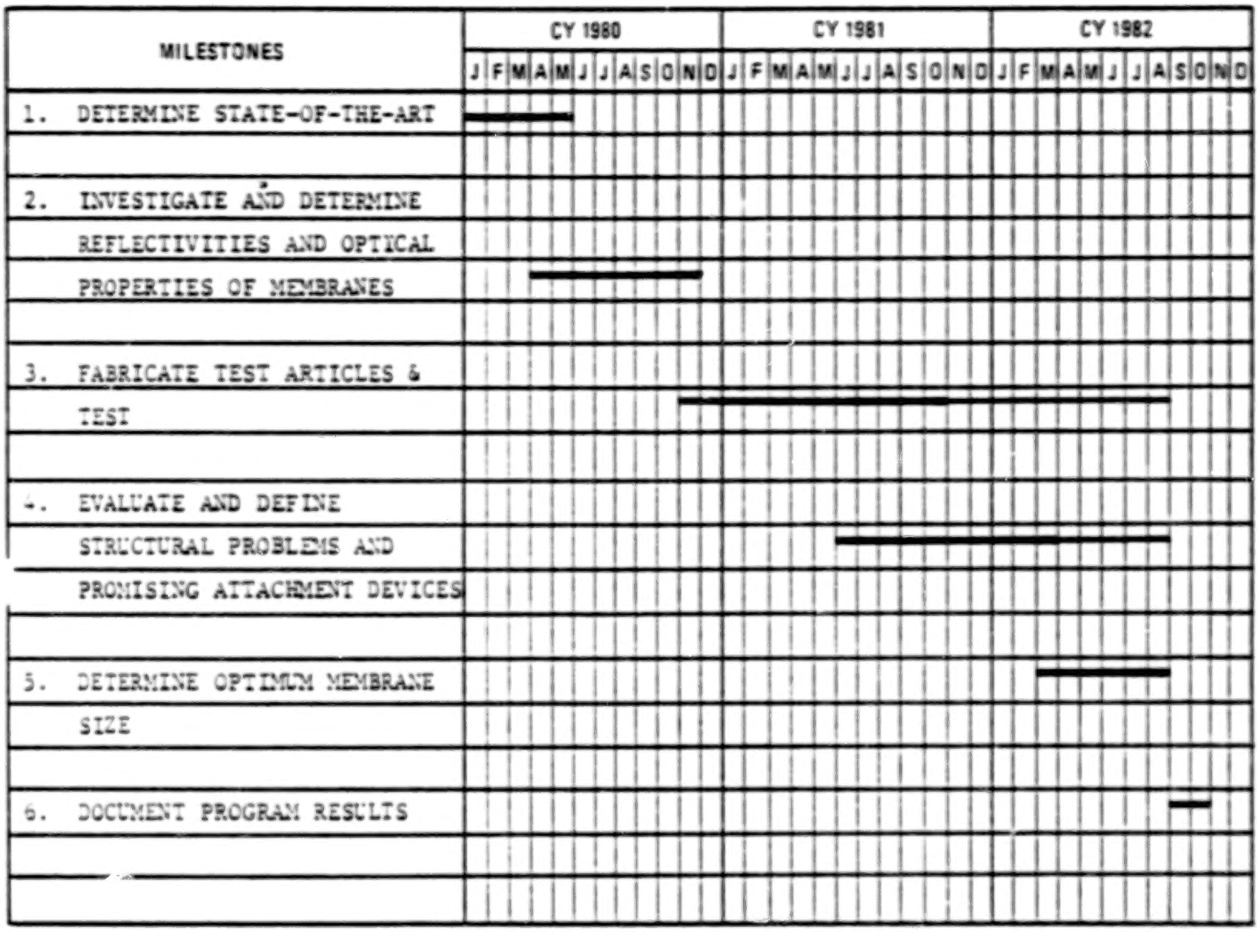
- APPROACH

Contact vendors and coating firms to determine the state-of-the-art of reflective thin film technology. Determine reflectivity values for thin film membranes based on coating thickness, surface properties, membrane tension, attachment devices, and manufacturing and deployment techniques. Determine tolerance variations on coatings and membrane thicknesses. Determine impact of membrane size and attachment device on reflectivity. Assess value of protective coatings and selective filters on reflector performance.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** REFLECTOR PERFORMANCE TESTS

- **MILESTONE SCHEDULE**



NOTES:

| RESOURCE REQUIREMENTS | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING | $100 K | $250 K | $150 K |
| • FACILITIES | | | |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** HIGH VOLTAGE (40 KV) SOLAR CELL STRING DESIGN

## JUSTIFICATION

High voltage solar arrays will be required to obtain a practical SPS design configuration. High voltage arrays have to be designed, developed and tested for space use. High voltage analytical and design data for solar arrays is non-existent for space applications. A design and development effort is required in order to obtain the basic technology data for use in the design and sizing studies for the SPS.

## TECHNICAL OBJECTIVES

Investigate the cell blanket design as to interconnections, dielectric strength, plasma leakage effects, and spacecraft charging isolation. Assess series parallel arrangements, effects of cell shadowing and variation in solar intensity on the array and voltage form.

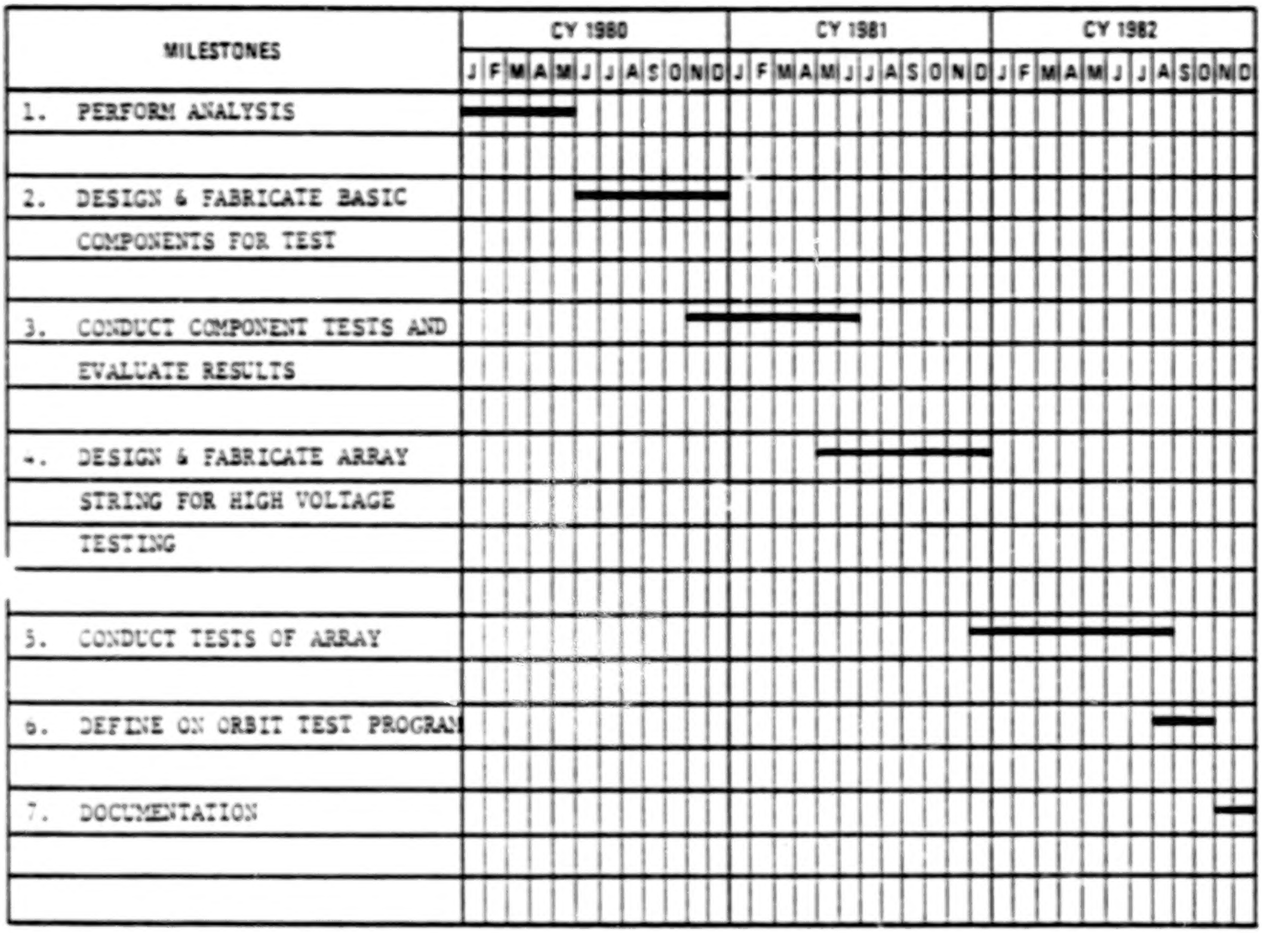
## APPROACH

Analyze and define potential problems of the baseline high voltage array. Configure, test and evaluate high voltage solar cell strings on typical blanket and structure configuration. Determine dielectric characteristics of array string as a function of voltage, materials of construction, and simulated on orbit environmental effects. Analyze and reduce test data for use in the design of high voltage solar arrays.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** HIGH VOLTAGE (40 KV) SOLAR CELL STRING

- **MILESTONE SCHEDULE**



NOTES:

- **RESOURCE REQUIREMENTS**

| | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING | $50 K | $50 K | $100 K |
| • FACILITIES | | TBD | TBD |

# SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- TECHNOLOGY TITLE SPS POWER DISTRIBUTION TECHNOLOGY

## • TECHNICAL SUMMARY

The primary objective of the PDS early research is to develop mathematical models of the overall PDS and to investigate lightweight approaches for high power/voltage dc to dc converters and switchgear. Mathematical models would be developed to evaluate load variations, spacecraft charging and transient effects upon the PDS. Non-magnetic (unique coupling) approaches for dc converters would be investigated to eliminate transformers and from experimental results extend weight projections from 0.5 kg/kW to 0.197 kg/kW. Switchgear research would demonstrate the validity of crossfield discharge tube switchgear concept and verify weight (.00682 kg/kW), efficiency (99.9%) and size 5 mW to (300 mW).

In addition, analyses will be performed to determine whether superconductivity is cost effective for SPS application and how it could be best utilized for power distribution. Various materials will be evaluated for use in slip-rings and brushes, including joining techniques for flat conductors.

## • TASK SUMMARY

| | $K |
|---|---|
| High Voltage/Current Transmission Simulation, dc Converter and Switchgear Investigation | 650 |
| Spacecraft Charging Analysis | 95 |
| Slip-Ring/Brushes Material Investigation | 120 |
| Flat Conductor Joining Processes Experiment | 60 |
| Superconduct. Cable Invest. | 125 |
| | $1050K |

- **TASK TITLE** HIGH-VOLTAGE/CURRENT TRANSMISSION SIMULATION

- **JUSTIFICATION**

With an orbiting power station, it is essential that load variations, transients and faults be determined so that proper control requirements can be established to insure continuous power transmittal to the ground station. It therefore, becomes essential that mathematical models be developed for computer simulation to investigate load variations, transients and fault detection schemes. The simulation would then aid in locating critical areas where sensors could be located so that proper corrective action could be taken. Two major goals for the SPS early research are weight reductions in dc converters down to 0.197 kg/kW and validation of a switchgear concept in terms of space application to achieve weight, efficiency, and size as required for the SPS.

- **TECHNICAL OBJECTIVES**

The objectives of the high voltage/current transmission simulation and component investigation's are as follows: (1) Develop mathematical models of components and loads; (2) Develop overall PDS mathematic model; (3) Investigate load variation effects; (4) Investigate transient effects; (5) Investigate fault detection (perform short circuit analysis); (6) Investigate EMI effects and where filtering should be employed; (7) Brassboard development and construction of a 10 kW dc converter to extend weight projection from 0.5 kg/kW to 0.197 kg/kW; and (8) Design and demonstrate brassboard switchgear to verify weight, efficiency, and size.

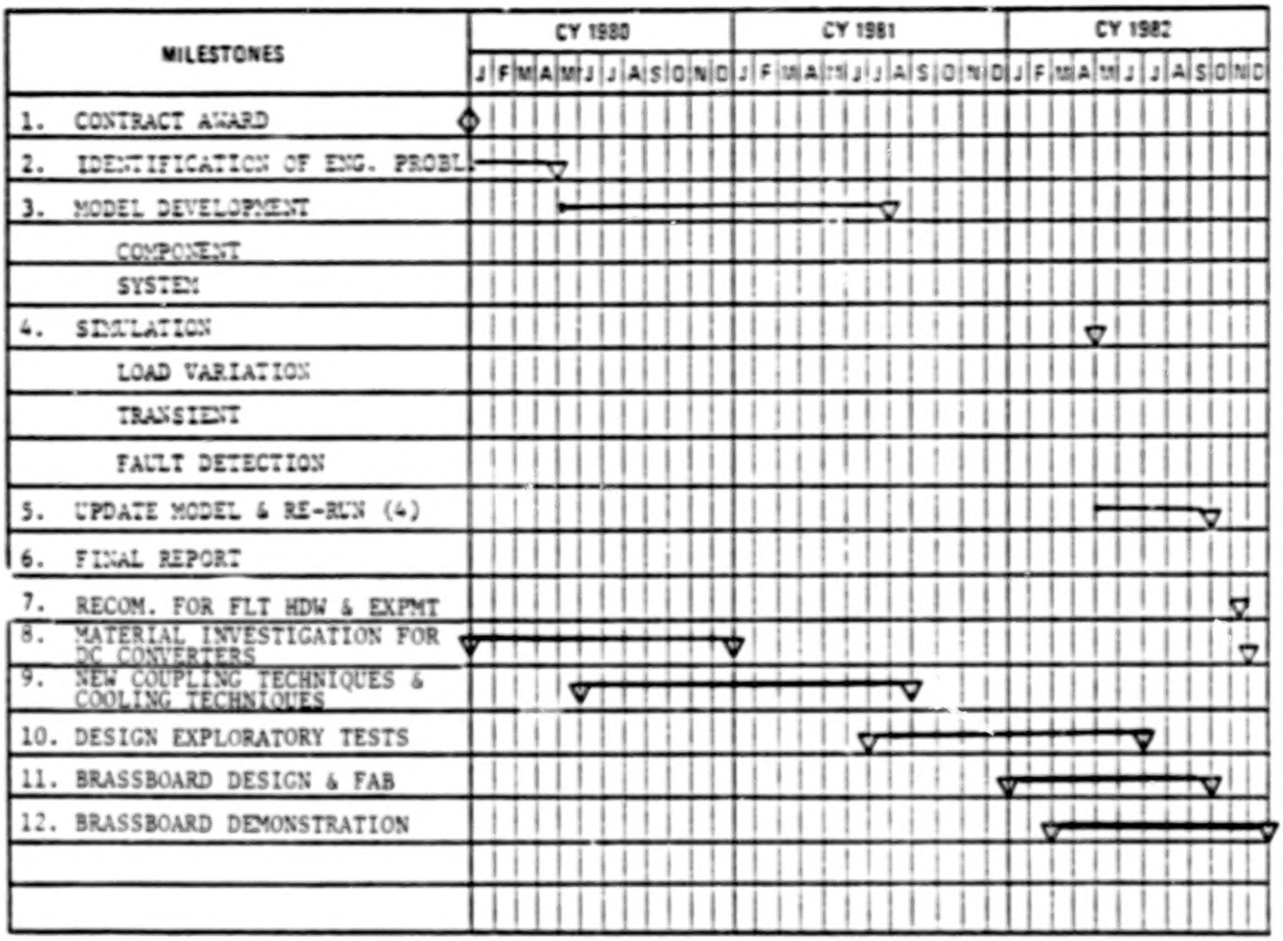
- **APPROACH**

This project will be divided into seven areas of investigation. The first will be to identify and enumerate the engineering problems which must be solved to establish the requirements and outputs of the simulation. The second consist of building the mathematical models for the simulator and to perform a baseline configuration run. The results will be reviewed and updated where necessary. In case of update, a rerun of the baseline will be performed. The third consists of the actual study phase of PDS, presentation of the solutions, and recommendations of changes as well as additions. The fourth consists of updating the models to the latest configuration and rerunning phase 3 to insure that the corrections made satisfies the requirements. The fifth deals with investigation of materials and candidate mechanizations of dc converter and switchgear designs, sixth is the design exploratory tests, seventh is the brassboards design and demonstration. Materials that will be investigated for the dc converters include lightweight high performance ferrites, composite hybrid materials, doping of conductors with oriented magnetic materials. In addition, investigations will be made of new semi-conductors for higher frequency, new coupling techniques and multiple function component technology, and cooling techniques. Switchgear design exploratory tests will be performed with available hardware prior to design and demonstration of brassboard design.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** HIGH-VOLTAGE/CURRENT TRANSMISSION SIMULATION

- **MILESTONE SCHEDULE**



NOTES:

- **RESOURCE REQUIREMENTS**

| | | FY 80 | FY 81 | FY 82 |
|---|---|---|---|---|
| • FUNDING | $K | 150 | 200 | 100 |
| • FACILITIES | | | | |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** SPACECRAFT CHARGING ANALYSIS

- **JUSTIFICATION**

In previous spacecraft vehicles, it has been found that under certain environmental conditions spacecraft charge affected various electronic functions. Some of these phenomenons have been investigated and reported. Since the SPS is required to transmit continuous power from the satellite to the ground, it is apparent that a spacecraft charge model be developed for determining spacing charge effects on the PDS and subsystems.

- **TECHNICAL OBJECTIVES**

1. Review existing spacecraft charge math models and determine how they could be implemented.
2. Develop spacecraft charging mathematical model for the SPS.
3. Perform coordination with simulation engineers for incorporating the spacecraft charge mathematical model into the overall PDS simulation model.

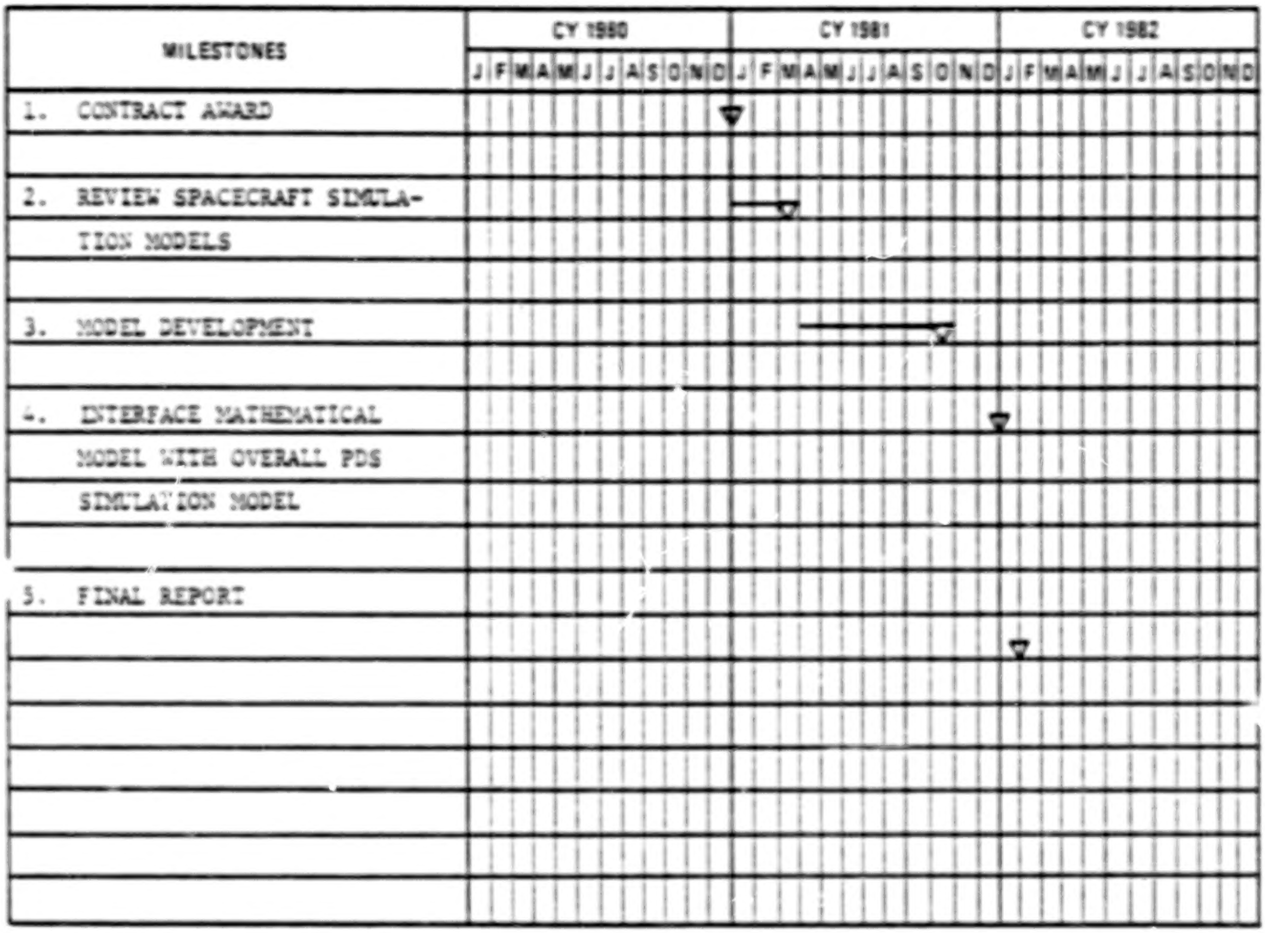
- **APPROACH**

This project will be divided into three phases. The first phase consists of a review of existing spacecraft simulation models to determine whether they could be utilized in the overall simulation model or whether new models would have to be developed for the SPS configuration. The second phases consists of developing a suitable mathematical model to be used in conjunction with the PDS overall mathematical model. After model has been completed, simulation will be made to confirm accuracy of model. The last phase consists of interfacing with simulation engineers for incorporating the model into the overall PDS simulation model and also participate in the simulation evaluation.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** SPACECRAFT CHARGING ANALYSIS

- **MILESTONE SCHEDULE**



1. CONTRACT AWARD
2. REVIEW SPACECRAFT SIMULATION MODELS
3. MODEL DEVELOPMENT
4. INTERFACE MATHEMATICAL MODEL WITH OVERALL PDS SIMULATION MODEL
5. FINAL REPORT

NOTES:

| RESOURCE REQUIREMENTS | | FY 80 | FY 81 | FY 82 |
|---|---|---|---|---|
| • FUNDING | $K | | 95 | |
| • FACILITIES | | | | |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** SLIP-RING/BRUSH MATERIAL INVESTIGATION

- **JUSTIFICATION**

Transfer of large amounts of power to high voltages and currents through slip rings has never been performed in space. Test and performance data of high power slip rings for space is critical to the successful design and operation of slip rings for the SPS.

- **TECHNICAL OBJECTIVES**

The objectives of the study consist of:

1. Analyze slip ring design concepts and determine potential materials to use for the slip rings and brushes.
2. Establish prototype model sizes, design components and fabricate for testing.
3. Perform laboratory test to determine electrical, mechanical and thermal characteristics of the slip ring and brush assembly.

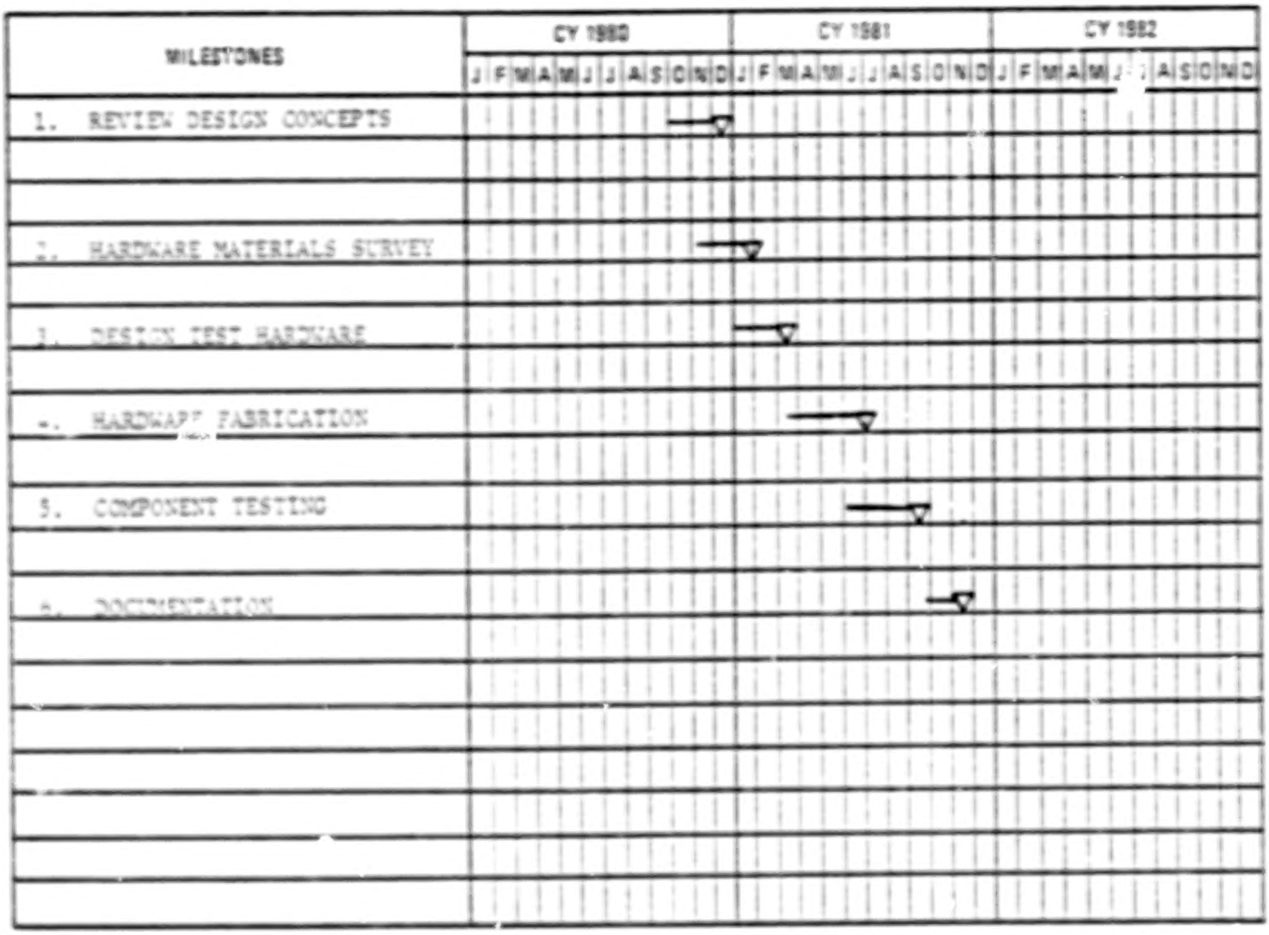
- **APPROACH**

1. Review design concepts of on orbit slip ring brush assemblies. Determine state-of-the-art of the technology and determine electrical, mechanical and thermal characteristics and performance of the design.
2. Discuss high voltage - high current slip ring requirements with vendors. Voltage drop, friction factors, wear rate, arcing, current density, brush pressure, and temperature effects are critical to the design of the slip ring brush assembly for long life and high performance.
3. Review SPS requirements and design prototype slip ring and brushes for testing.
4. Perform laboratory testing of prototype components and correlate test data with analytical design results.
5. Document results of the study and test programs.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** SLIP RING/BRUSH MATERIAL INVESTIGATION

- **MILESTONE SCHEDULE**



NOTES:

- RESCURCE REQUIREMENTS

| | $K | FY 80 | FY 81 | FY 82 |
|---|---|---|---|---|
| • FUNDING | | | 120 | |
| • FACILITIES | | | | |

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## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** FLAT CONDUCTORS JOINING PROCESSES EXPERIMENT

- **JUSTIFICATION**

In SPS power distribution systems, flat conductors are preferred because they exhibit better heat dissipating qualities than round conductors. However, because of the length of these conductors, they appear hard to handle, therefore sectionalization is a necessity. The joining of these sections could alter the characteristics of the conductors, therefore it becomes important to investigate various joining processes to determine which will produce the optimum joint.

- **TECHNICAL OBJECTIVES**

The objectives of the study are.

1. Determine most feasible joining process.
2. Determine electrical and thermal characteristics.
3. Determine mechanical characteristics and strength of the joint.

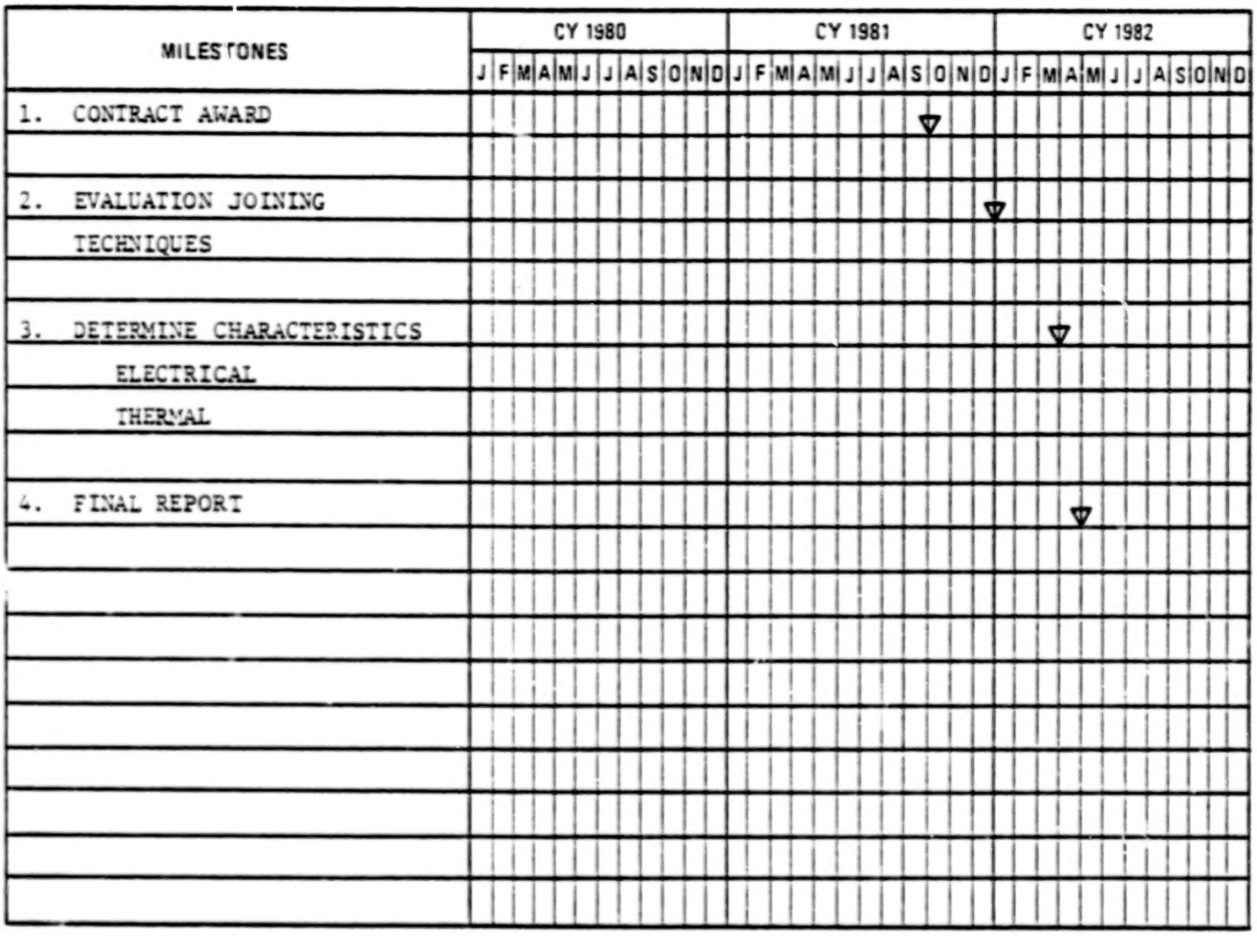
- **APPROACH**

1. Review existing flat conductor cable joining concepts. Establish SPS cable sizes and determine number of joints that may be needed.
2. Evaluate the various joining techniques such as conductive adhesives, mechanical clamping and/or weldments for potential use on the SPS.
3. Design prototype joint for potential application to the SPS and fabricate.
4. Conduct tests to determine electrical and mechanical performance and strength. Assess ease of on orbit assembly and reliability of joint.
5. Document the results of the study and test program.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** FLAT CONDUCTORS JOINING PROCESSES EXPERIMENT

- **MILESTONE SCHEDULE**



NOTES:

- **RESOURCE REQUIREMENTS**

| | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING $K | | | 60 |
| • FACILITIES | | | |

# SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** SUPERCONDUCTING POWER CABLE INVESTIGATION

- **JUSTIFICATION**

With orbiting satellites it is very important that numerous schemes be investigated for possible reduction of the overall power and distribution weight so that transportation cost could be minimized. One such scheme is the utilization of superconductive cables. A cursory analysis indicated that with such technique a reduction of approximately 1/2 in conductor weight could possibly be achieved.

- **TECHNICAL OBJECTIVES**

The objectives of the study would be to:

1. Develop exact mathematical physics of the superconductive state to determine design and performance parameters for high current conductor elements.
2. Analyze liquid and vapor helium thermal transfer configuration.
3. Design the cryogenic refrigeration subsystem and transport cooling loop superconductive conditions.
4. Investigate a control system for maintaining a 9° Kelvin state at the conductor site.

- **APPROACH**

1. Investigate and analyze the superconducting cables. Calculate heat leaks, operating temperatures, and cable sizes as a function of current carrying capacity, conductor length and materials of construction. Determine feasible and theoretical critical temperatures, and safety requirements.
2. Based on the preliminary cooling capacity requirements, investigate refrigeration concepts and machinery and size the system. Determine volume, weight, coefficient of performance, and system capacity. Establish radiator size and integrate with SPS configuration.
3. Evaluate control requirements for cryogenic and superconducting subsystems.
4. Document study results.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** SUPERCONDUCTING POWER CABLE INVESTIGATION

- **MILESTONE SCHEDULE**

| MILESTONES | CY 1980 |  |  |  |  |  |  |  |  |  |  |  | CY 1981 |  |  |  |  |  |  |  |  |  |  |  | CY 1982 |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | J | F | M | A | M | J | J | A | S | O | N | D | J | F | M | A | M | J | J | A | S | O | N | D | J | F | M | A | M | J | J | A | S | O | N | D |
| 1. CONTRACT AWARD |  |  | ▽ |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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| 2. SUPERCONDUCTIVITY FACILITY STUDY |  |  |  |  |  |  |  |  |  | ▽ |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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| 3. DESIGN OF COOLING SYSTEM FOR MAINTAINING SUPERCONDUCTIVE CONDITIONS |  |  |  |  |  |  |  |  |  |  |  |  |  |  | ▽ |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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| 4. DESIGN CONTROL SYSTEM |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | ▽ |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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| 5. FINAL REPORT & RECOMMENDATIONS |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | ▽ |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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NOTES:

- **RESOURCE REQUIREMENTS**

|  |  | FY 80 | FY 81 | FY 82 |
|---|---|---|---|---|
| • FUNDING | $K | 75 | 50 |  |
| • FACILITIES |  |  |  |  |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TECHNOLOGY TITLE** SPS STRUCTURES TECHNOLOGY

- **TECHNICAL SUMMARY**

The objective of this experimental research is to develop technology associated with specific aspects of the structural subsystem of an SPS (Solar Power System). Optimum structural element shapes will be developed based on design, analysis and test data. Advanced composite material systems will be selected for SPS structures, applications and mechanical properties of those systems will be developed. Mathematical simulations of SPS configurations, utilizing test determined stiffnesses, damping valves, etc., will be generated and subjected to simulated operational environments to determined "as designed" structural integrity including operational stress levels and satellite distortions. SPS structure construction scenarios will be generated, construction equipment defined and conceptually designed, and a plan generated for the ground and on-orbit technology development of this equipment. Attitude and figure control technology and ACS propulsion system research is also included in this effort.

- **TASK SUMMARY**

| | $K |
|---|---|
| Beam Element Optimization | 200 |
| Materials Development | 400 |
| Numerical Characterization | 500 |
| Construction Equipment Development | 500 |
| Attitude and Figure Control Techniques for Flexible Large Structures | 500 |
| Total | 2100 |

- **TASK TITLE** BEAM ELEMENT OPTIMIZATION

- **JUSTIFICATION**

At the heart of an SPS (Satellite Power System) large space structure is the beam element fabricated on-orbit by a beam builder or machine. This beam element consists of ultra thin-walled lightweight cap sections, transverse struts, and diagonal braces combined to form an open triangular shape from either aluminum or composite materials. The allowable operating stress, $\sigma$, is a function of both general buckling and local crippling of the selected material as influenced by the operating temperature and eccentricities caused by temperature gradients through the section, manufacturing irregularities and joint efficiencies. Optimized specific strength can only be determined by design variations supported by detailed mathematical simulation coupled, finally, with hardware testing.

- **TECHNICAL OBJECTIVES**

Develop optimized cap and transverse strut configurations compatible with:

- Materials
- Beam Builder Concepts
- Force and Torque Levels
- Ground Processing Techniques

- **APPROACH**

This task will consist of three (3) phases conducted serially. The first phase will be directed toward - establishing the design requirements and criteria for a beam element based on existing study results from all government and industry sources.

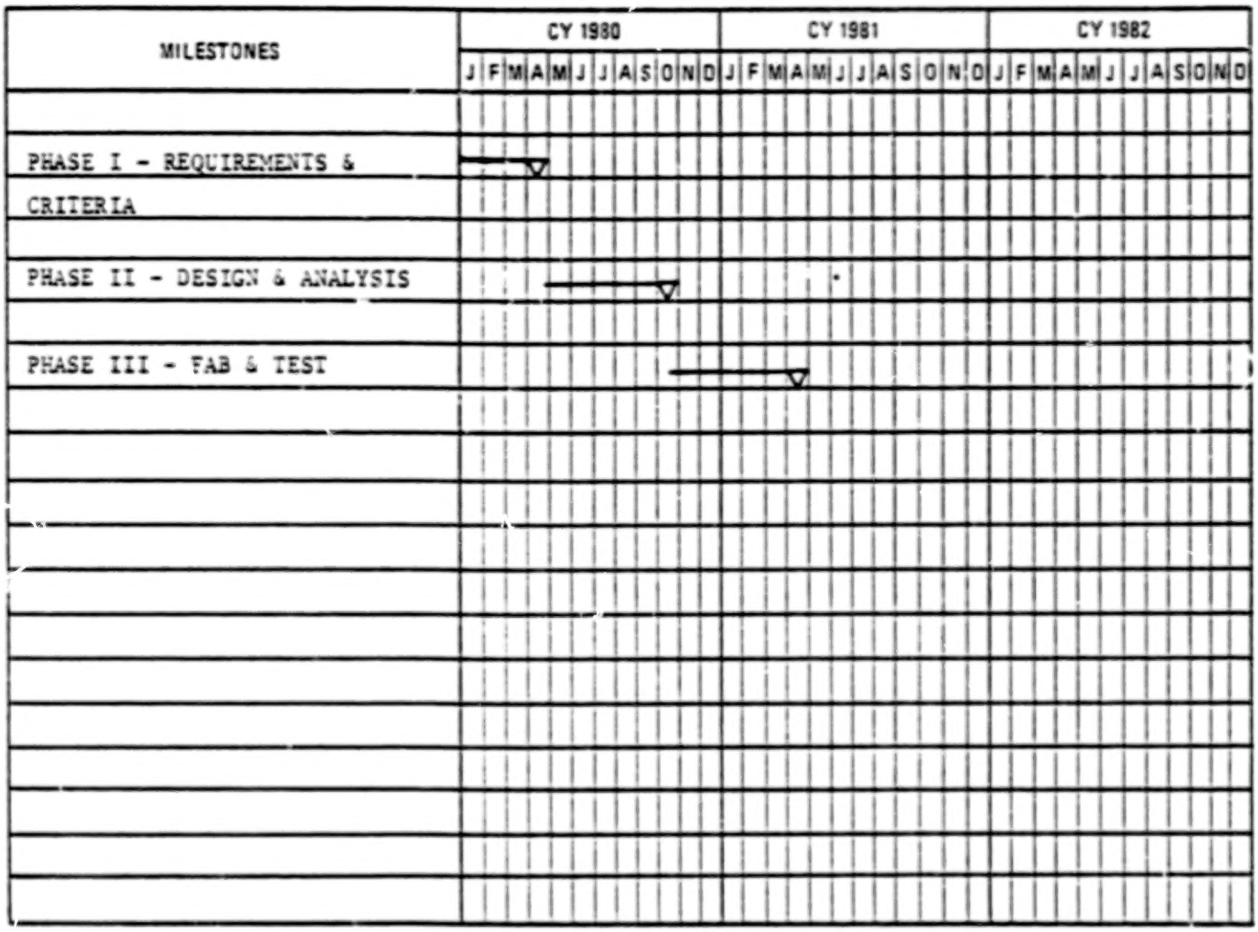
The second phase will be an iterative design and analysis process. This will result in one or more potentially optimum designs for both the longitudinal cap section and the transverse strut including joining details.

The third phase will consist of the fab and test of the design/s resulting from Phase 2.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** STRUCTURAL DESIGN CRITERIA AND VERIFICATION

- **MILESTONE SCHEDULE**



NOTES:

| • RESOURCE REQUIREMENTS | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING | 150 K | 50 K | |
| • FACILITIES | YES | YES | NO |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** MATERIALS DEVELOPMENT

- **JUSTIFICATION** Advanced composite material systems have a high potential for extensive application to SPS and other large space structures. Their high specific stiffness, low coefficient of thermal expansion (α) and the low energy required to form and weld or bond them together make them extremely attractive from a technical point of view. Operational thermal environments (>300°F) that would eliminate aluminum alloy as a structural material would also eliminate state-of-the-art composite systems such as graphite/epoxy and dictate the use of an advanced high temperature system that uses a matrix material such as polyimide based resin. The requirement for on-orbit fabrication may dictate a composite system that is classified as a thermoplastic rather than the thermosetting systems used for aerospace structures today. To apply these advanced systems to a detailed SPS structure design will require that a complete set of mechanical properties data be generated to supply the designer and structural analyst with material design allowables.

- **TECHNICAL OBJECTIVES**

Develop a design data guide for candidate advanced composite material systems with the greatest potential for application to an SPS structural subsystem. This data guide will be similar in concept and level of depth to "Metallic Materials & Elements for Aerospace Vehicle Structures (MIL-HDBK-5B)".

- **APPROACH**

This program will consist of three (3) phases conducted serially. The first phase will be the development of material requirements and criteria based on results of existing Government and aerospace contractor SPS systems studies. This will consist primarily of determining the environment the materials will be subjected to throughout the mission from launch to end of life.

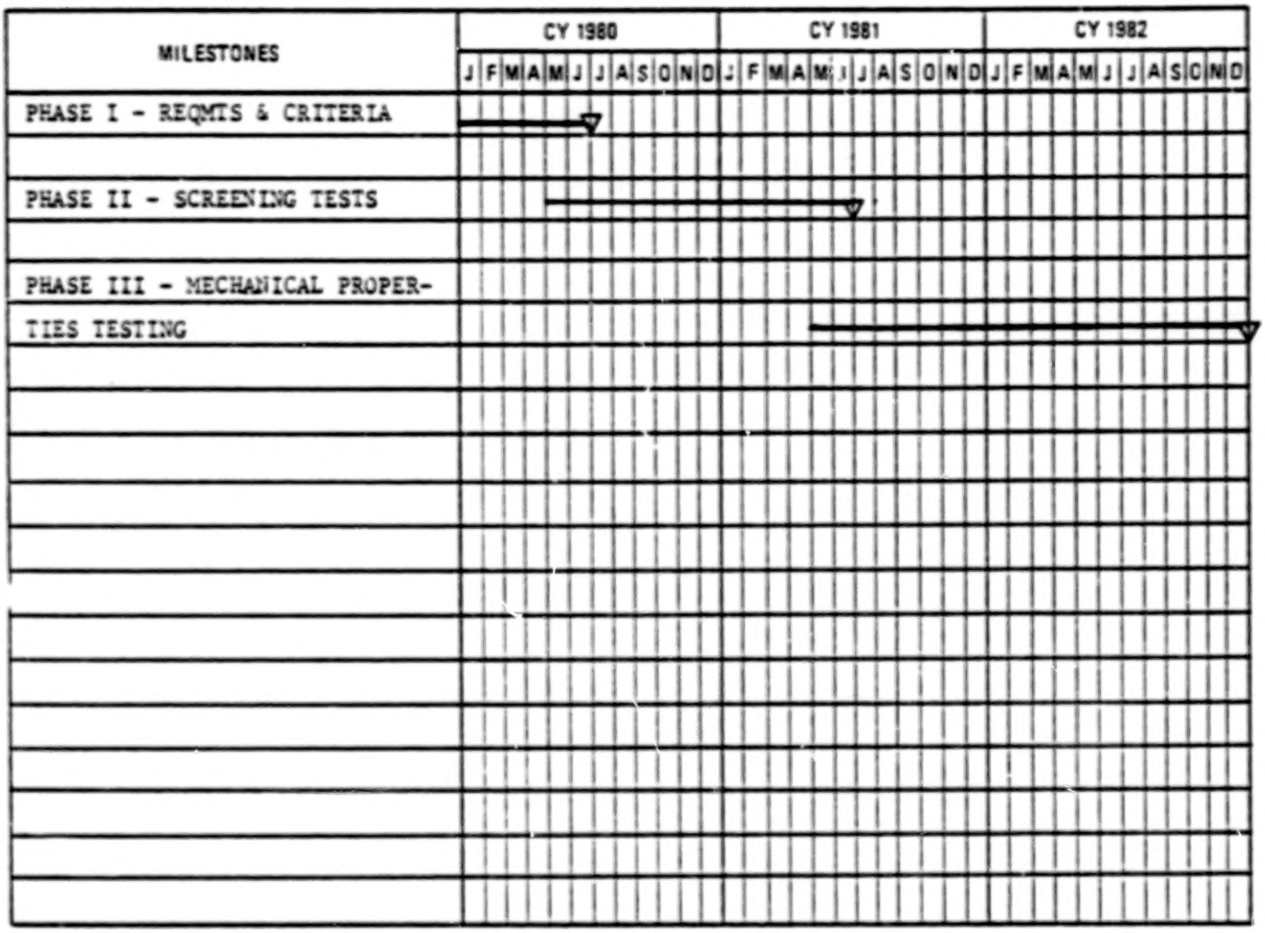
Phase II will consist of material screening tests resulting in the selection of advanced composite material systems with the highest potential for application in the environmental regime established in phase I.

Phase III will be the conduct of extensive mechanical properties testing to develop 3 σ design allowables consistent with standard ASTM methods. The result will be a design data guide for use in detailed SPS structure design.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** MATERIALS DEVELOPMENT

- **MILESTONE SCHEDULE**



NOTES:

- **RESOURCE REQUIREMENTS**

|  | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING | $100 K | $150 K | $150 K |
| • FACILITIES |  |  |  |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** NUMERICAL CHARACTERIZATION

- **JUSTIFICATION** Essential to the success of the SPS system is its structural integrity during assembly and operation. The SPS being very large and very complex, is not amenable to ground qualification test verification hence it will demand accurate analytical methods to determine loads, stresses, and dynamic behavior. Such a large and complex system must employ computer methods to determine such items as the dynamic behavior of the structure for control and the responses from the control system; the induced loads from antenna motion; the effects of rapid thermal transients; deflection of the system for pointing accuracy; member sizes for required system stiffnesses; and other related structural behavior. To use the computer programs will require a math model of the system. The size and complexity of the system will require that the model be made in steps and built up from the subelements to the overall system, and particularly for the use in the dynamic analysis that some degrees of freedom be omitted, yet accurately represent the final structure. The antenna structure, particularly the netting structure, must be modeled separately, since the stiffness of support structure and the stiffness of the webbing are orders of magnitude apart, causing ill-conditioned matrices within the computer programs. Once the structural models are complete and in use, they must be updated and refined based on test data from both earth and space test programs which deal with difficult predictable factors as joint stiffness, crippling stresses, shape factors for loading and buckling of very long thin sections, eccentricities due to manufacturing and assembly, and changes in structural properties due to local thermal variations.

- **TECHNICAL OBJECTIVES**

  - Develop subelement and component models for SPS structure for use in loads, stress, thermal, and dynamic analyses.
  - Verify analytic structural behavior of SPS subelement and components with test results.
  - Refine and update the computer structural model due to both analytic and test results.
  - Use of the structural model as an effective design aid in the design and analysis of a lightweight, long-life, and an efficient structural system for the SPS and similar large space structures.

- **APPROACH** This task will be accomplished in four overlaying phases. Phase I will consist of the modeling of the basic subelement structural members to determine their stiffness due to their lightweighted (cutouts) design configuration. In addition, Phase I will include a study to determine which major computer program, Nastran or Stardyne, should be used. Two problems exist in the Nastran program. The first is a method to handle the pretension X-tie bracings when the bracing goes into compression. The second problem is the inability of Nastran to handle beam elements with running loading and stress recovery thereof.

Phase II, using the results of Phase I, will consist of the modeling of the major components using substructuring methods. The antenna structure (webbing and equipment support by the webbing) will be treated as a separate unit, and not included in the overall structural system due to its very low stiffness compared to the rest of the structure. However, the effects of the antenna webbing and mass will be included in the overall system model. Both stress and dynamic models will be prepared.

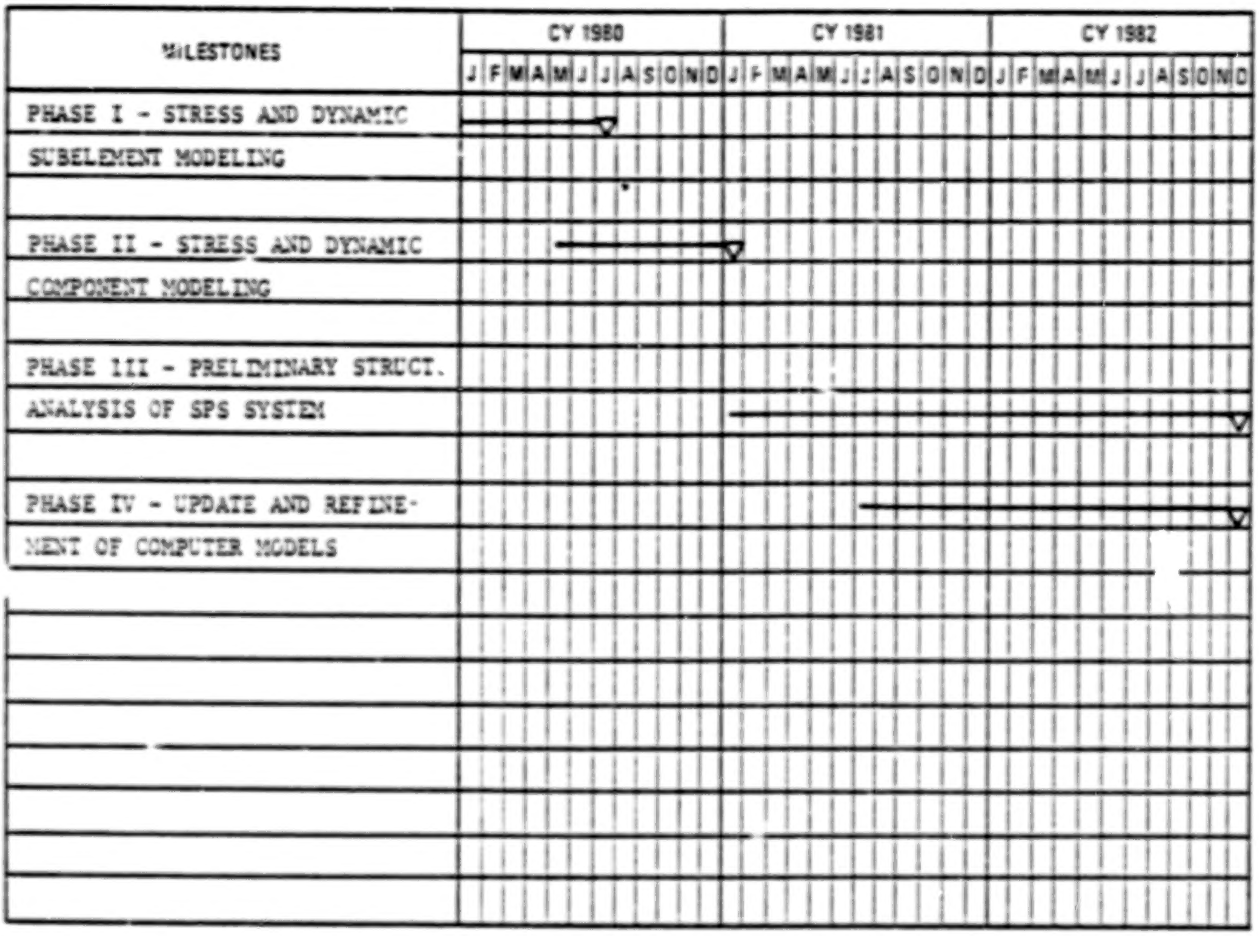
Phase III will be the analytical phase. In this phase, using the stress and dynamic models, various loading and thermal profile cases will be run to check out the structural behavior of the system, both for stress and dynamics. The results will be iterated to determine control properties, removal of undesirable dynamic characteristics, the preliminary sizing of the members, determination of deflections of the structure during assembly and operating life, and the behavior of the structure under rapid changes in thermal environments.

Phase IV will overlap Phase III, using the results of tests which will determine the effects of joint connections, material properties under long-life conditions, crippling and buckling behavior of long extra-thin sections, and other related data; the computer program models will be altered and updated. In addition, the computer program models will be used to predict the behavior of test articles. After testing, the computer results and test results will be compared, with test results being incorporated into the models.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** NUMERICAL CHARACTERIZATION

- **MILESTONE SCHEDULE**



PHASE I - STRESS AND DYNAMIC SUBELEMENT MODELING

PHASE II - STRESS AND DYNAMIC COMPONENT MODELING

PHASE III - PRELIMINARY STRUCT. ANALYSIS OF SPS SYSTEM

PHASE IV - UPDATE AND REFINEMENT OF COMPUTER MODELS

NOTES:

| RESOURCE REQUIREMENTS | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING | $100 K | $200 K | $200 K |
| • FACILITIES | - | - | - |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** CONSTRUCTION EQUIPMENT DEVELOPMENT

- **JUSTIFICATION** Because of its massive size, the success of an SPS (Satellite Power System) is dependent on the ability to accomplish a major portion of the construction activity on-orbit. On-orbit construction will necessarily require the early definition of construction equipment so that their early technology verification development activity can be defined and accomplished in a time frame compatible with other phases of the program. The beam builder is an example of on-orbit construction equipment. Almost every SPS study conducted by NASA and the aerospace industry has identified this piece of equipment as being necessary and requiring early development. The identification of other construction equipments, which may be even more complex than the beam builder must be accomplished in the near term future. To do this, an SPS configuration must be selected and subjected to a detailed construction scenario that will identify this equipment.

- **TECHNICAL OBJECTIVES**

  Identification and preliminary design of SPS on-orbit construction equipment along with a plan for the ground and on-orbit technology development activity.

- **APPROACH**

  This project will consist of three overlaying phases. Phase I will consist of the development of an end-to-end construction scenario starting with payload modules as delivered to the construction site and ending with the completed construction of the satellite structure and operational equipment.

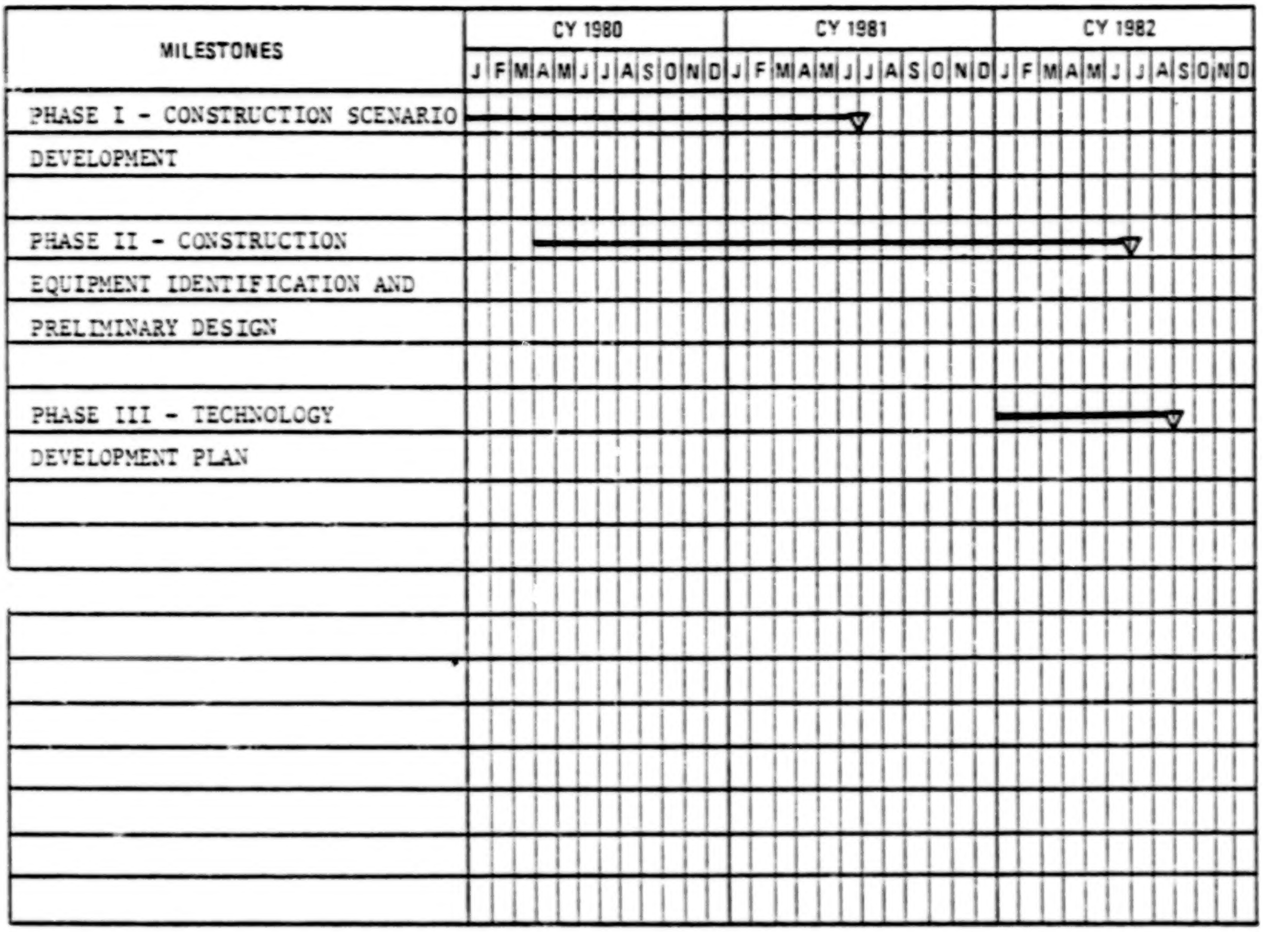
  Phase II will consist of the identification and preliminary design of construction equipment necessary to support the scenario developed in phase I.

  Phase III will consist of the preparation of a detailed ground and on-orbit technology development plan for each piece of equipment identified in phase II.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** CONSTRUCTION EQUIPMENT DEVELOPMENT

- **MILESTONE SCHEDULE**



NOTES:

| • RESOURCE REQUIREMENTS | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING | $200 K | $200 K | $100 K |
| • FACILITIES | | | |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** ATTITUDE & FIGURE CONTROL TECHNIQUES FOR FLEXIBLE LARGE STRUCTURE

- **JUSTIFICATION** Traditionally the achievement of satisfactory control system/structural dynamic performance and stability has been achieved through the use of analytical and ground testing techniques to confirm modeling assumptions and uncertainties. With the extremely large, lightweight and flexible SPS structures full-scale dynamic testing is precluded. Hence, greater reliance must be placed on analytical techniques and subscale model testing to minimize expensive dynamic flight testing requirements. The different nature of the SPS structure warrants an investigation to define preferred dynamic modeling techniques and requirements for new modeling developments.

Figure Control - The requirements for figure control increase rapidly as a function of the concentration ratio (CR) of the solar collector. Higher CR's for photovoltaic collectors are desirable to minimize the cost of solar cell blankets. The introduction of bending sensors and electromechanical activators are the typical approach to figure control. New concepts such as a semi-passive "thermally activated expansion joint" concept offers promise as a low cost approach for SPS. Simple design techniques to minimize thermal bending also warrant investigation.

Attitude Control - For SPS new modeling and analytical tool developments are required to:

1. More accurately represent the flexibility of this class of structure.
2. Incorporate the dominant disturbances into the structural bending such as the gravity-gradient and the thermal bending excitation which can be the dominant control system excitation.
3. To facilitate the application of the new developments in modern control theory which are appropriate to the control of large flexible spacecraft.

- **TECHNICAL OBJECTIVES**

Figure Control - Define preferred structural concepts, passive design criteria to minimize structural distortion, and rationale for locating structural actuators. Define the relative merits of new unique figure control actuators and compare with contemporary electromechanical actuators. Define the preferred approaches for SPS.

Attitude Control - Define structural dynamic modesl for control system analysis that accurately represent SPS structural concepts; develop automated computer tools for control system analysis; and define preferred control software techniques to minimize undesirable dynamic interaction and flight test requirements to confirm the structural modeling.

- **APPROACH**

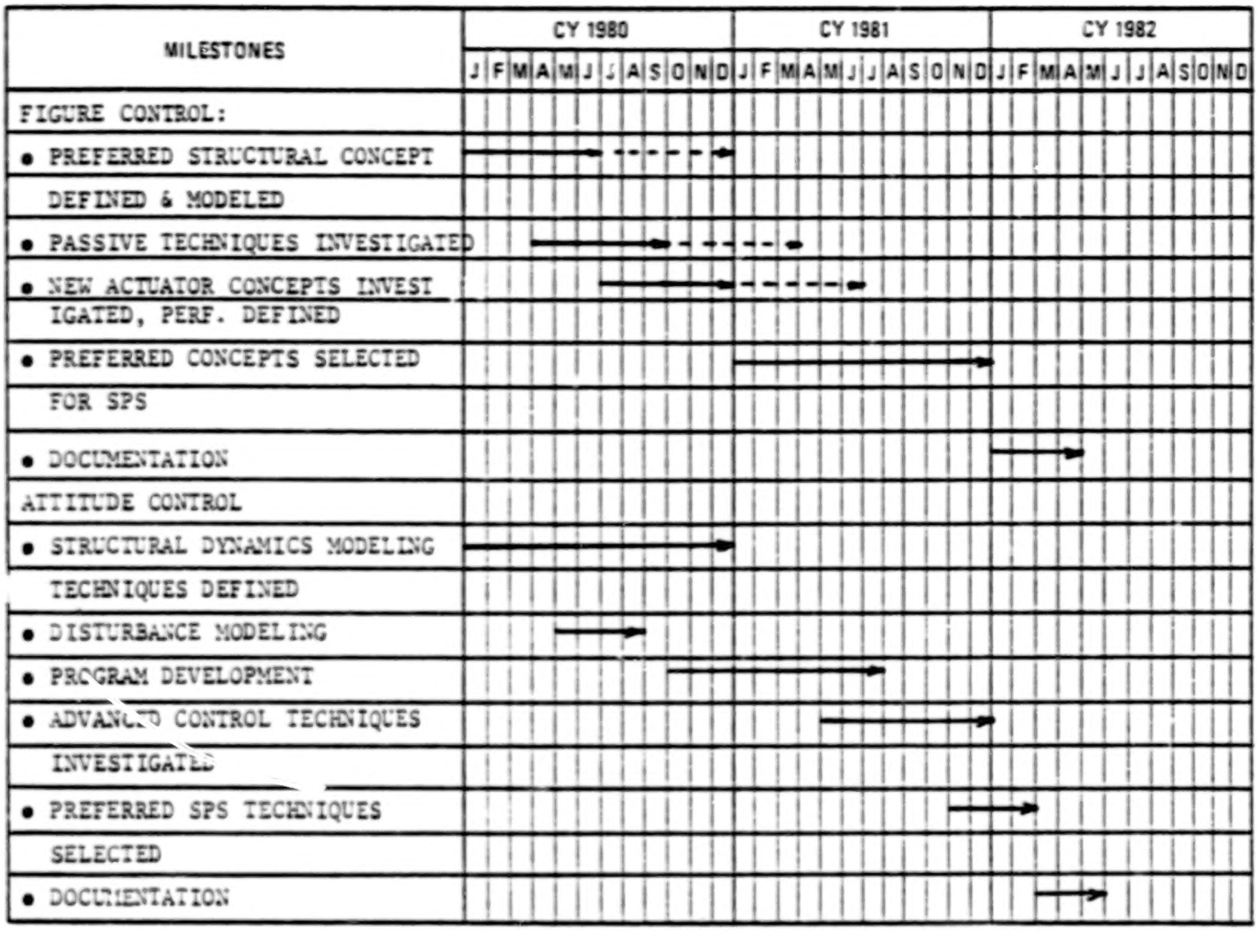
Figure Control - Define passive structural techniques to minimize thermal deformation and alignment techniques to minimize assembly misalignments. Define preferred locations for structural actuators, their requirements and alignment accuracies achievable. Investigate the design and performance achievable with new figure control actuator concepts such as the semi-passive "thermally controlled expansion joint." Define the preferred structure and figure concepts for SPS.

Attitude Control - Investigate the requirements for new structural dynamics modeling techniques and preferred approaches including the new disturbance models appropriate to SPS (gravity-gradient and thermal bending disturbances). Develop automated control system/structural dynamics analysis programs appropriate for these higher order systems. Investigate the application of modern control theory to minimize adverse structural dynamic interaction. Define the requirements for simple technology verification flight tests to confirm the modeling.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** ATTITUDE & FIGURE CONTROL TECHNIQUES FOR FLEXIBLE LARGE STRUCTURE

- **MILESTONE SCHEDULE**



NOTES:

- **RESOURCE REQUIREMENTS**

| | | FY 80 | FY 81 | FY 82 |
|---|---|---|---|---|
| • FUNDING | Figure Control | 100 K | 125 K | 65 K |
| | Attitude Control | 75 K | 100 K | 35 K |

- FACILITIES

- TECHNOLOGY TITLE SPS PROPULSION TECHNOLOGY

- TECHNICAL SUMMARY

The Rockwell proposed horizontal takeoff heavy lift launch vehicle (HTO-HLLV) utilizes hydrogen fueled multicycle air-breathing engine systems (MC-ABES) during flight through the sensible atmosphere. The MC-ABES are required to efficiently operate over a Mach range from 0 to 7 and an altitude of 0 to 120,000 ft. The primary areas requiring analyses and technological advancement include engine cycle performance and lightweight fuel cooled engine and inlet structures/components. The objective is to synthesize a MC-ABES with an installed minimum thrust/weight of 10 and an average net fuel specific impulse of approximately 4000 sec. The ABES cycles requiring evaluation and integration include turbojet, air-turbo exchanger (air-turbo rocket) and ramjet.

An argon ion propulsion EOTV is another essential element in the SPS mass transfer system. Argon ion thruster and power module laboratory testing is required to improve designs and minimize refurbishment requirements.

- TASK SUMMARY

| | |
|---|---|
| 1. Multicycle Airbreather Engine System (MC-ABES) Analysis and Component Development | $1,500 K |
| 2. ACS Electric Propulsion Development | 1,000 K |
| 3. Argon Ion Thruster and Power Module Laboratory Testing | 700 K |
| | $3,200 K |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** SPS TRANSPORTATION SYSTEM - MULTICYCLE AIRBREATHER ENGINE SYSTEM (MC-ABES) ANALYSES AND COMPONENT DEVELOPMENT

- **JUSTIFICATION**

The SPS earth to LEO operational transportation system is a major contributor to overall program cost. The development of a suitable MC-ABES could meet the needs of a fully recoverable/reusable horizontal earth launch vehicle which would drastically reduce overall SPS transportation systems cost.

- **TECHNICAL OBJECTIVES**

Synthesize and analyze MC-ABES with a minimum thrust/weight (installed) of 10 to 1 and a minimum average net specific impulse of 4000 sec.

Identify specific MC-ABES components and subsystems requiring technology development.

Initiate critical component development and testing programs. Components or subsystems will be at the laboratory or "breadboard" level.

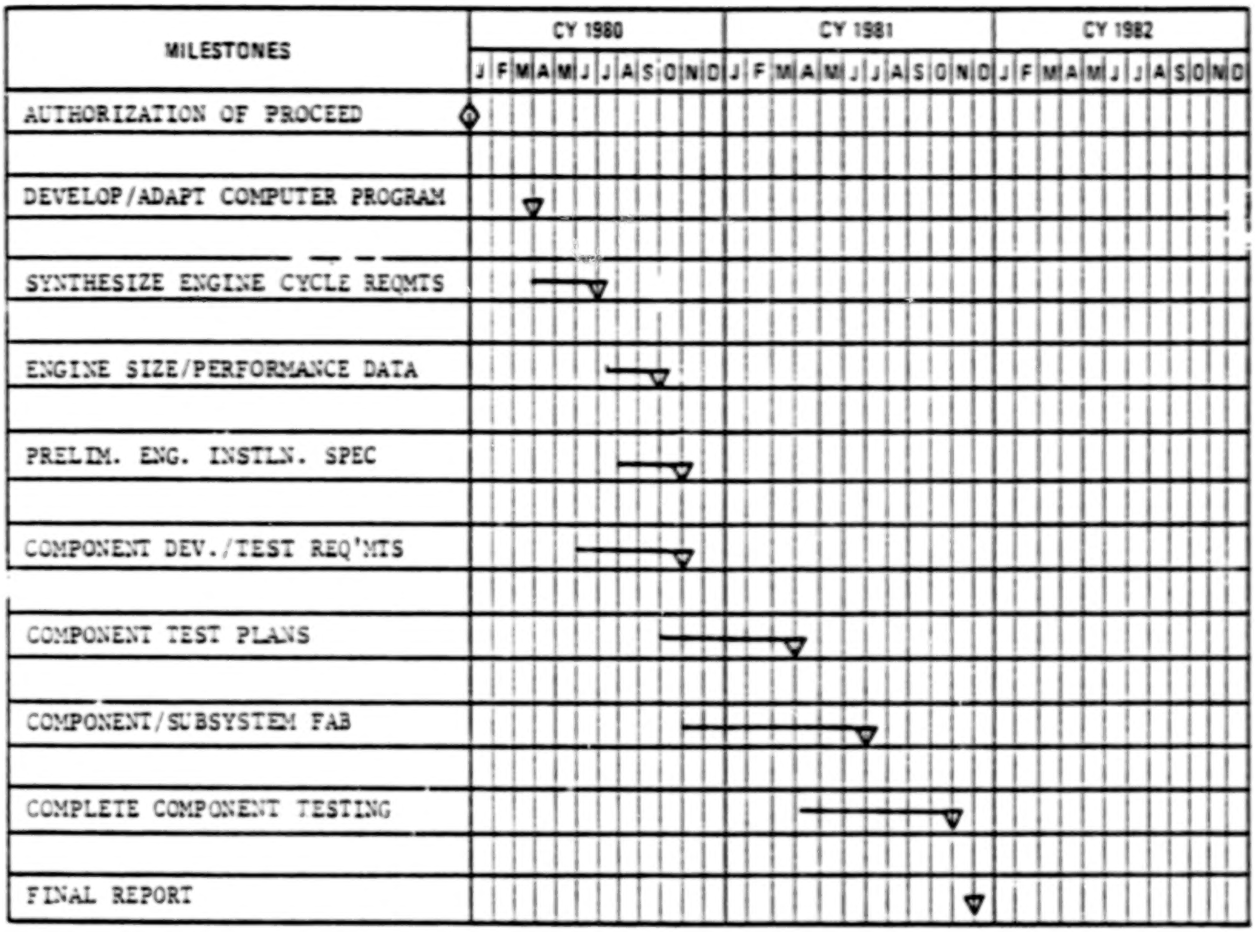
- **APPROACH**

Develop/adapt MC-ABES cycle performance computer programs. Based upon the computer analyses, synthesize a MC-ABES capable of providing the required thrust and performance. Conduct performance sensitivity analyses and identify critical areas and components requiring technological development. Prepare component and subsystem design, development and test plans and requirements. Conduct laboratory and/or breadboard model testing to the level required to provide the necessary technological base to assure the successful design/development of the required flight hardware prototype. The design and development of the flight hardware is not a part of this task. Prepare a preliminary MC-ABES specification.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** SPS TRANSPORTATION SYSTEM - MULTICYCLE AIRBREATHER ENGINE SYSTEM (MC-ABES) ANALYSES AND COMPONENT DEVELOPMENT

- **MILESTONE SCHEDULE**



NOTES:

| • RESOURCE REQUIREMENTS | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING | 250 K | 1.25 M | |
| • FACILITIES | NONE | NONE | |

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** ACS ELECTRIC PROPULSION DEVELOPMENT

- **JUSTIFICATION** The '76 & '77 SPS study effort clearly established the desirability of high performance ($I_{sp} \geqq 13,000$ sec.), long life, low cost electric propulsion for use in the SPS Attitude Control & Stationkeeping Subsystem (ACSS) and for the Electric Orbit Transfer Vehicle (EOTV).

Performance: The high performance electric propulsion for the EOTV was found to result in very substantial cost savings relative to a chemical OTV. For the SPS spacecraft the stationkeeping & attitude control functions were found to require high performance propulsion in order to prevent very large propellant resupply costs over the satellite lifetime.

Thruster Life: The currently estimated argon ion thruster lifetime of 5000 operating hours will result in large cost penalties for thruster replacement and/or refurbishment. Techniques to extend the lifetime of the thruster grids so as to minimize the overall cost (initial plus servicing) should be pursued.

(Check against EOTV Task)

Thruster Power Processing: Traditional electric thruster power processing electronics are quite massive and expensive. Techniques to utilize relatively raw power from the solar arrays and simpler control electronics to satisfy the thrusting requirements of the SPS spacecraft application require further investigation in order to define reliable, low cost power processing techniques equipment.

Cryogenic Propellant Storage: The storage of the argon propellant as a cryogen (rather than as a gas) will appreciably reduce tank mass and transportation costs for propellant delivery. The cryogenic propellant storage systems require durther design analysis to define preferred design concepts.

- **TECHNICAL OBJECTIVES**

1. Define thruster design parameters, servicing requirements, power processing techniques and propellant storage design techniques to minimize the overall electric propulsion subsystem costs (hardware plus propellant resupply costs) for the EOTV & the SPS satellite RCS.
2. Confirm the performance & lifetime characteristics of the electric thrusters with ground based testing.
3. Develop a flight demonstration thruster for flight verification of performance and lifetimes.

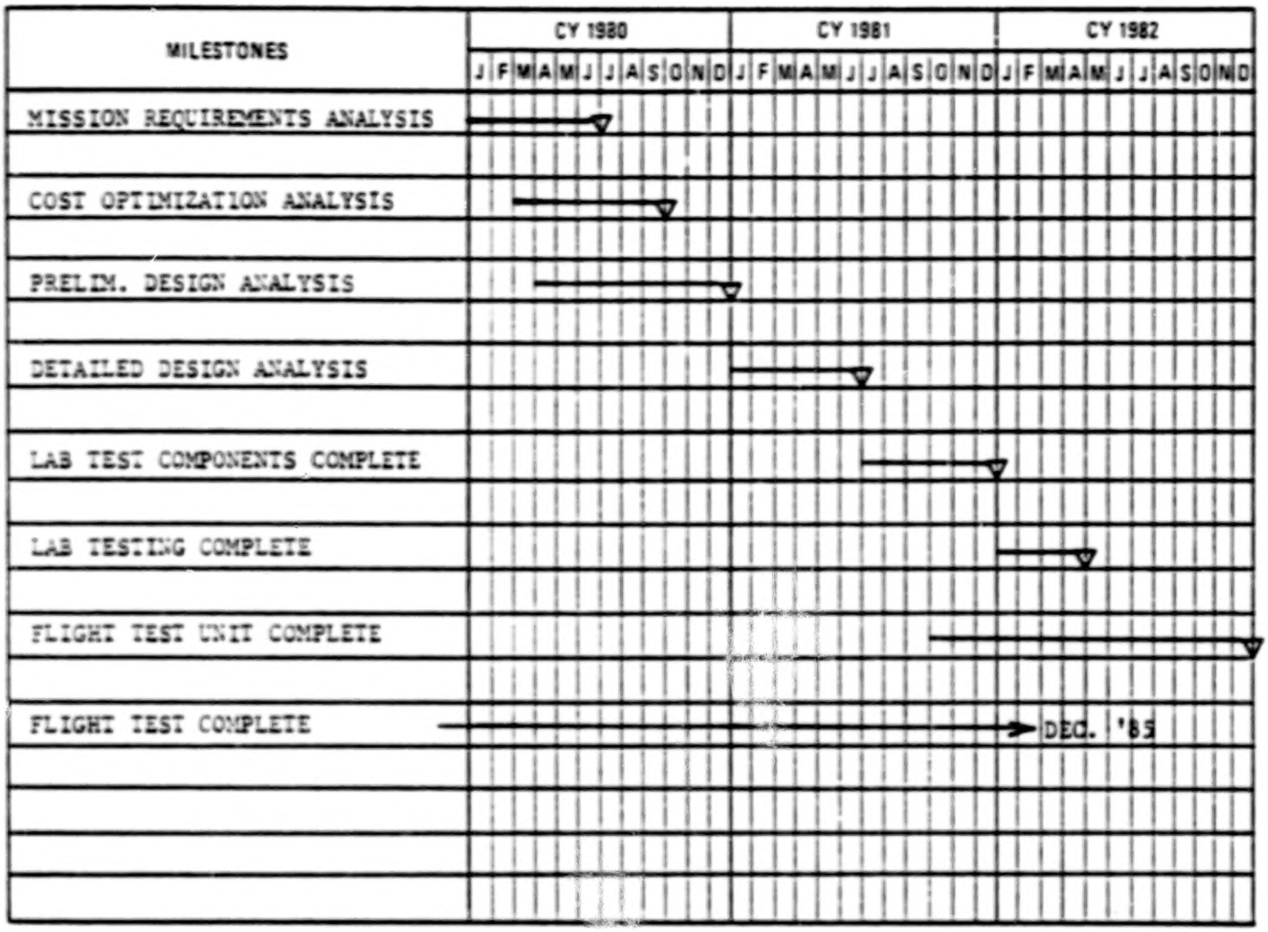
- **APPROACH**

1. Perform mission requirements analyses and cost optimization studies to define the most cost effect thruster subsystem design parameters.
2. Perform preliminary and detailed thruster designs for ground and flight verification tests.
3. Perform ground and flight tests to confirm the thruster performance and lifetime characteristics.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** ACS ELECTRIC PROPULSION DEVELOPMENT

- **MILESTONE SCHEDULE**



NOTES:

- **RESOURCE REQUIREMENTS**

| | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING | 300 K | 350 K | 350 K |
| • FACILITIES* | | | |

*NASA LeRC FACILITIES SUGGESTED

# SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** ARGON ION THRUSTER AND POWER MODULE LABORATORY TESTING

## JUSTIFICATION

The EOTV argon ion propulsion system can only operate efficiently (competitively and advantageously) if refurbishment requirements can be minimized. It appears from work done at LeRC that thruster modules can be designed that will operate for decades without excessive deterioration, or a need for refurbishment, except for the accelerating grid sets. The grids are subject to positive ion bombardment, etc., and will require periodic refurbishment. A major redesign of thruster modules is therefore required. This involves not only removable grid sets, but also possibly new materials, laboratory models, and supporting tests.

## TECHNICAL OBJECTIVES

- Complete a EOTV mission analysis that reveals the set of desired thruster operating characteristics: i.e., specific impulse, thrust, trip time, fleet size, payload, electric power profiles, and refurbishment cycles.
- Conceptually design and size thrusters that satisfy the required thruster characteristics of the mission analysis.
- Design and verify, with a simulated arrangement, a practical means of replacing thruster grids (several at one time) with the use of manipulator arms or some other arrangement.
- Design and build a laboratory thruster module (one or more as required) which incorporates the refurbishable grid system selected from the simulated arrangement.
- Test the thruster module to establish thrust, beam divergence, effectiveness of beam neutralization, and grid deterioration rates, etc.

## APPROACH

a. It is the task of the mission analysts to determine the preferred set of thruster operating characteristics, i.e., accelerating voltage (specific impulse), beam current (thrust), trip times (LEO to GEO, GEO to LEO), refurbishment cycles, solar blanket BOL power, mean electrical output, annealing cycles and methods, payload per EOTV trip, number of HLLV launches per SPS in GEO, thruster lifetime, etc.

It is necessary to study the gross scenario in order to determine minimum over-all cost and to flatten cost peaks. A sensitivity study is also required to minimize program perturbations from material shortages or supply problems.

b. The conceptual design and sizing will be carried out so as to overlap with the requirements (mission) analysis. It is anticipated that the facilities and expertise associated with LeRC will be employed.

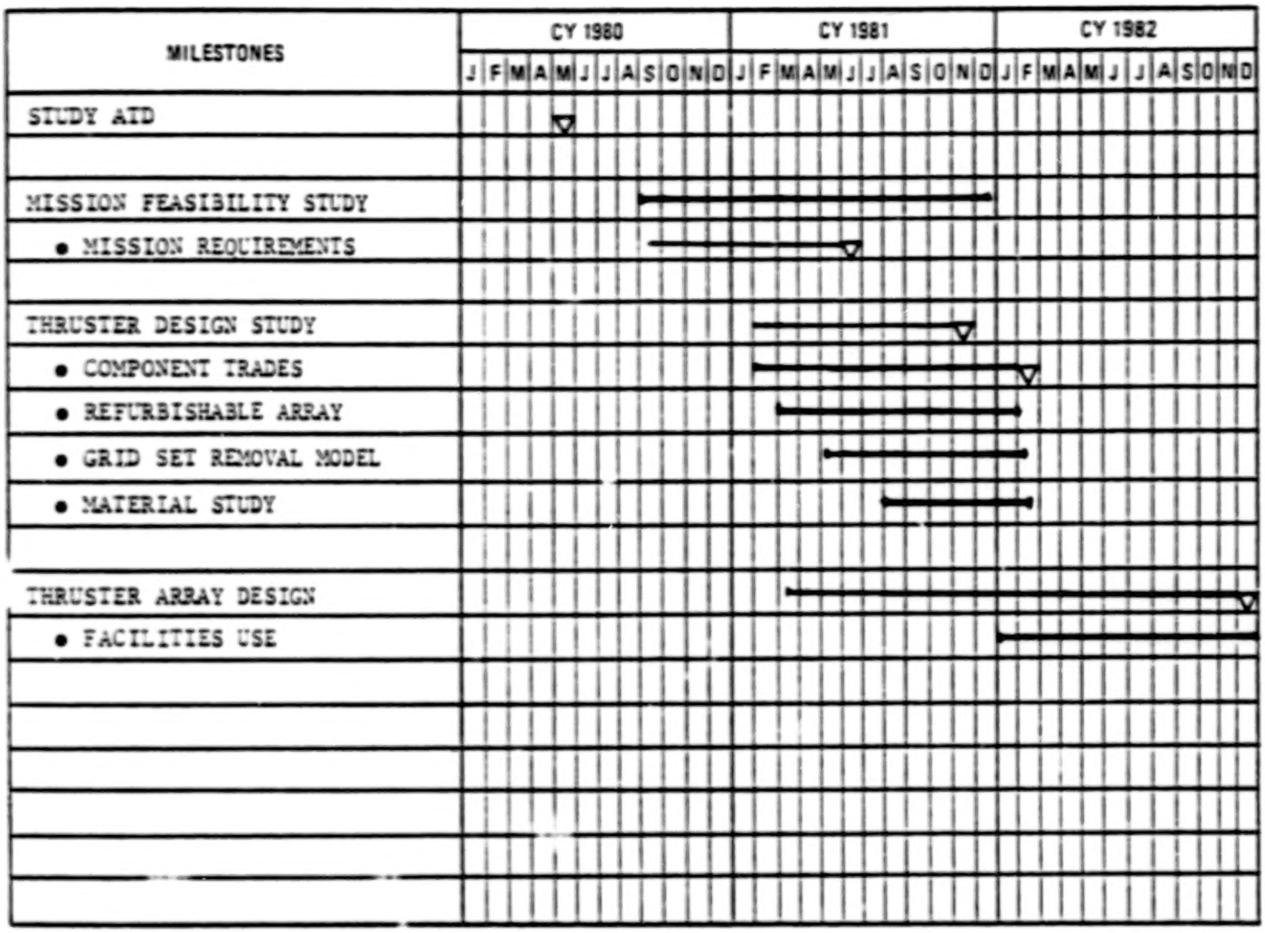
c. It is required that the grids be removable from the front. For example, each grid might be held in place by a compressed spring much like a bayonet light bulb. In this case a simulated manipulator would push the grid in axially, twist it 90°, and then pull it out. This task therefore must examine the problem of grid refurbishment i.e., replacing the expended grid with a new or refurbished grid. Preferably an entire group of grids should be replaced as a unit.

d. It is anticipated that the construction and testing of an actual thruster will be done at LeRC. Verification of thrust, beam divergency, neutralization effectiveness, etc., are typical measurements that would be desirable. A pendulum arrangement for estimating thrust is available at LeRC.

## SPS SUPPORTING RESEARCH & TECHNOLOGY TASK PLAN

- **TASK TITLE** ARGON ION THRUSTER AND POWER MODULE LABORATORY TESTING

- MILESTONE SCHEDULE



NOTES:

| RESOURCE REQUIREMENTS | FY 80 | FY 81 | FY 82 |
|---|---|---|---|
| • FUNDING | 150 K | 250 K | 300 K |
| • FACILITIES | | YES | |

# APPENDIX A

# SPS ADVANCED GaAs SOLAR CELL DEVELOPMENT

## A.1 INTRODUCTION

The technical and programmatic analyses to date show the Satellite Power System (SPS) to be technically feasible and economically viable. These assessments are based on use of advanced photovoltaic power conversion devices. Both silicon (Si) and gallium aluminum arsenide (GaAs) solar cell materials have been proposed.

The GaAs photovoltaic subsystem has the potential of low weight, increased performance, higher resistance to ionized radiation levels, and the ability to operate with concentrators with minimum loss in performance compared to Si cells and it should actively be developed. The specific solar cell characteristics are strong "drivers" to the satellite system design. Key cell parameters and their impacts on the SPS technical viability are summarized in Table A-1. Each parameter value shown is critical to obtaining a competitive satellite system.

The concern is that if gallium arsenide solar cells with these parameters are not available, the silicon alternative solar cell with its achievable characteristics will result in an SPS that is marginal or submarginal in acceptability (i.e., economic viability). GaAs solar cell development must be actively undertaken to determine the achievability of required performance and cost characteristics. Major decisions must be made early in the SPS program relative to continued efforts in the area of solar cell development. It is believed that by the end of FY 1980 it is necessary to have the answers to a number of technical questions to enable NASA/DOE decision-makers to recommend on the future of SPS.

Major issues to be investigated and resolved in this proposed study to aid in decision-making include the following:

1. Projected Solar Cell Efficiency - Resolving the issue of interface losses between the active gallium arsenide and the sapphire substrate.

2. Sapphire Ribbon Thin-Film Producibility - Technical and economic feasibility of producing 20 μm thick continuous sapphire ribbon with high-level quality control.

3. Raw Material Costs - Compounds utilized in the MO-CVD process (with improved purities).

4. Technical Viability of Alternatives to GaAs/$Al_2O_3$ (Sapphire) GaAs Cell Configuration - Includes peeled film technology and other substrates such as germanium.

Table A-1. *SPS Solar Cell Parameters as Design Drivers*

| Parameter | SPS GaAs Design Values | Description | Impact on Design (failure to achieve values) |
|---|---|---|---|
| Cell efficiency | 20% (AM0, 28°C)<br>9 | SPS concept (CR=2) requires $30.6 \times 10^6$ m$^2$ of solar cells; array output: 336.6 W/m$^2$ | Lower efficiency penalizes:<br>● Array area<br>● Weight<br>● Array cost<br>● Transportation cost<br>● Construction schedule<br>Silicon performance could be as low as 123.6 W/m$^2$ |
| Radiation degradation | 4% | Non-annealable allowance is 4% array area; current design assumes self-annealing at $\geq$ 125°C | Failure to achieve annealing will penalize array area 16% for GEO operations and 40% EOTV; silicon degradation penalties still greater |
| Weight | 0.252 kg/m$^2$ | Total SPS array weight = $7.536 \times 10^6$ kg; $\sim$25% of total satellite weight | Substitution of silicon penalizes system by $22.2 \times 10^6$ kg or more |
| Operating temperature | $\geq$ 125°C | GaAs performance at ops temp. $\sim$18% (concentration ratio = 2.0) | Lower performance could penalize system by forcing a nonconcentrated SPS $\sim 4.06 \times 10^6$ kg; $18.8 \times 10^6$ m$^2$ solar cells |
| Cost | \$70.82/m$^2$ solar cells | Total array cost \$3130.2 $\overline{M}$ (basic cell/reflector cost \$2320 $\overline{M}$) per satellite (includes transportation, structures, power distributed, and cell/reflectors)* | Silicon cell cost penalty adds \$2126.7 $\overline{M}$ to array cost* |
| Cell thickness | 5 μm active GaAs region<br>20 μm sapphire substrate | Gallium requirement for SPS $\sim$375 metric tons (5 GW). | Thicker materials impact weight, cost, and availability |

*Reference: Satellite Power System (SPS) Concept Definition Study (Exhibit C) First Quarterly Review. Rockwell International, SD 78-AP-0075 (June 21-22, 1978)

5. **Degradation** - Radiation degradation and determination of self-annealing certainty.

6. **Producibility** - Whether low-cost solar cells can be produced for the rate and quantity of SPS requirements, for both early verification program and operational program.

## A.2 OBJECTIVE AND SCOPE

The objective of this proposed program is to carry out experimental investigations to provide the technical data necessary to support a system recommendation by DOE at the close of 1980 regarding the technical viability of advanced gallium arsenide solar cells for the SPS program. The program will cover a two-year period of performance with an anticipated ATP early in 1979. The major scope of the program involves experimental and analytical investigations of cell structure, cell modeling, design and performance analysis, cell fabrication and characterization, cell radiation test and analysis, material improvements, and manufacturing processes.

A study flow logic diagram is shown in Figure A-1, showing each task and proposed output. A proposed task breakdown structure is shown in Figure A-2. The tasks are designed to provide answers to the technical questions that need to be answered before GaAs solar cells can be selected as the SPS solar cell for further development.

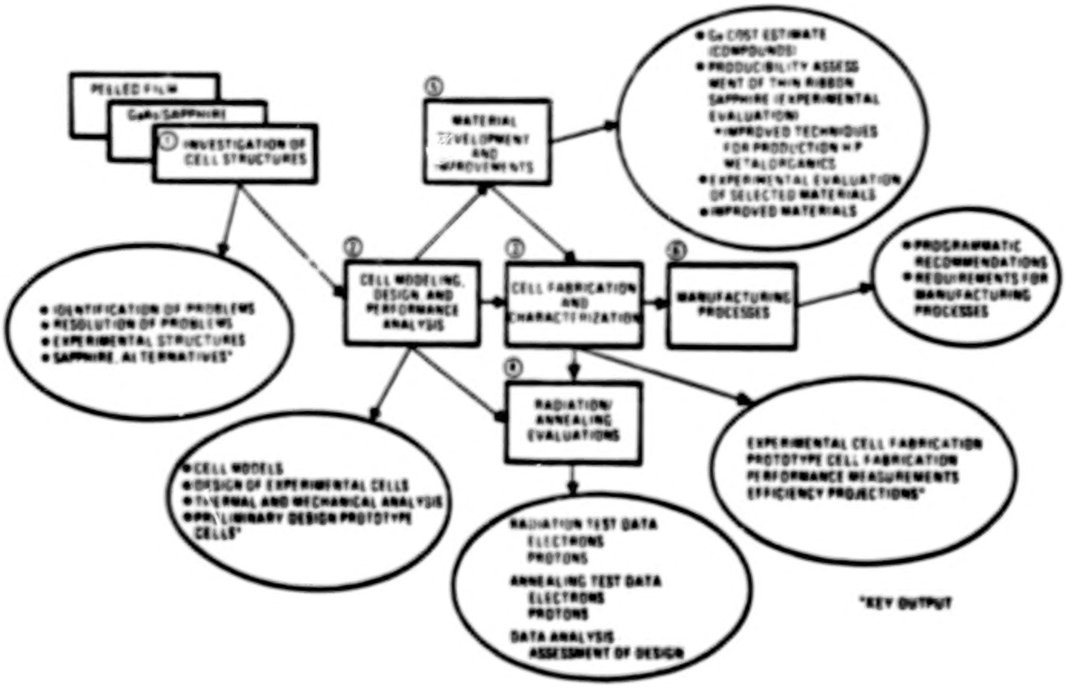

PEELED FILM
GaAs/SAPPHIRE
① INVESTIGATION OF CELL STRUCTURES
• IDENTIFICATION OF PROBLEMS
• RESOLUTION OF PROBLEMS
• EXPERIMENTAL STRUCTURES
• SAPPHIRE, ALTERNATIVES*
⑤ MATERIAL DEVELOPMENT AND IMPROVEMENTS
• Ga COST ESTIMATE (COMPOUNDS)
• PRODUCIBILITY ASSESSMENT OF THIN RIBBON SAPPHIRE (EXPERIMENTAL EVALUATION)
• IMPROVED TECHNIQUES FOR PRODUCTION H.P METALORGANICS
• EXPERIMENTAL EVALUATION OF SELECTED MATERIALS
• IMPROVED MATERIALS
② CELL MODELING, DESIGN AND PERFORMANCE ANALYSIS
③ CELL FABRICATION AND CHARACTERIZATION
⑥ MANUFACTURING PROCESSES
• PROGRAMMATIC RECOMMENDATIONS
• REQUIREMENTS FOR MANUFACTURING PROCESSES
④ RADIATION/ ANNEALING EVALUATIONS
• CELL MODELS
• DESIGN OF EXPERIMENTAL CELLS
• THERMAL AND MECHANICAL ANALYSIS
• PRELIMINARY DESIGN PROTOTYPE CELLS*
RADIATION TEST DATA
ELECTRONS
PROTONS
ANNEALING TEST DATA
ELECTRONS
PROTONS
DATA ANALYSIS
ASSESSMENT OF DESIGN
EXPERIMENTAL CELL FABRICATION
PROTOTYPE CELL FABRICATION
PERFORMANCE MEASUREMENTS
EFFICIENCY PROJECTIONS*
*KEY OUTPUT

*Figure A-1. Study and Flow Outputs*

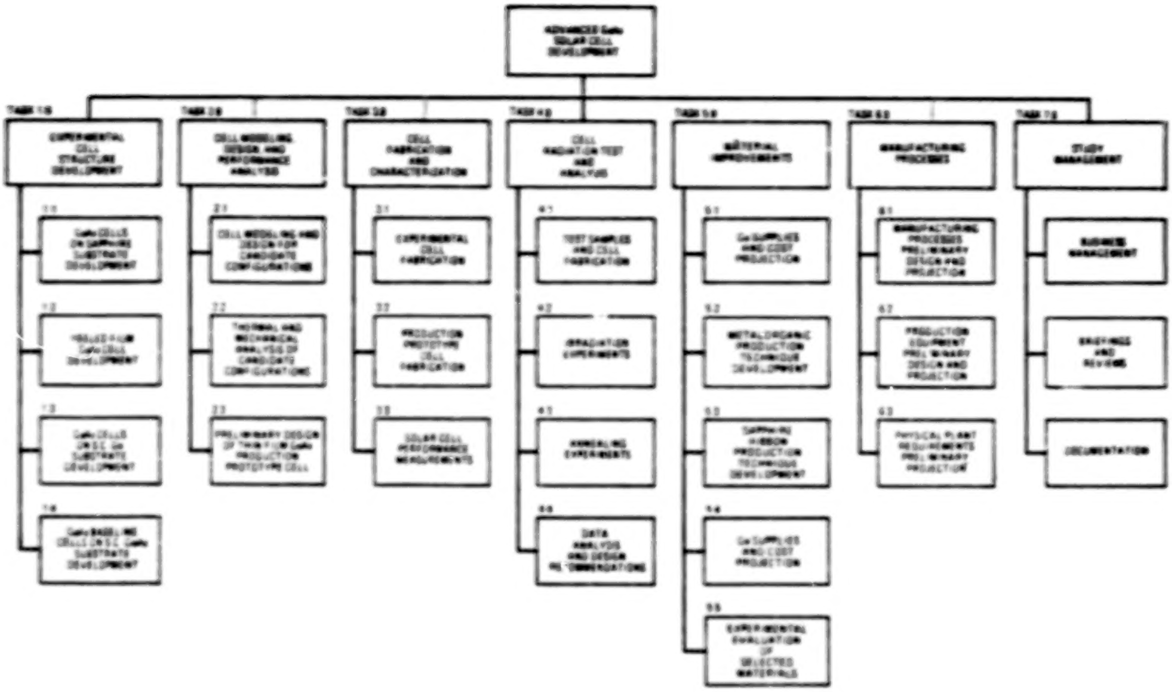

ADVANCED GaAs SOLAR CELL DEVELOPMENT
TASK 1.0
EXPERIMENTAL CELL STRUCTURE DEVELOPMENT
1.1
GaAs CELLS ON SAPPHIRE SUBSTRATE DEVELOPMENT
1.2
GaAs CELL DEVELOPMENT
1.3
GaAs CELLS ON S.C. Ge SUBSTRATE DEVELOPMENT
1.4
GaAs BASELINE CELLS ON S.C. GaAs SUBSTRATE DEVELOPMENT
TASK 2.0
CELL MODELING DESIGN AND PERFORMANCE ANALYSIS
2.1
CELL MODELING AND DESIGN FOR CANDIDATE CONFIGURATIONS
2.2
THERMAL AND MECHANICAL ANALYSIS OF CANDIDATE CONFIGURATIONS
2.3
PRELIMINARY DESIGN OF THIN FILM GaAs PRODUCTION PROTOTYPE CELL
TASK 3.0
CELL FABRICATION AND CHARACTERIZATION
3.1
EXPERIMENTAL CELL FABRICATION
3.2
PRODUCTION PROTOTYPE CELL FABRICATION
3.3
SOLAR CELL PERFORMANCE MEASUREMENTS
TASK 4.0
CELL RADIATION TEST AND ANALYSIS
4.1
TEST SAMPLES AND CELL FABRICATION
4.2
IRRADIATION EXPERIMENTS
4.3
ANNEALING EXPERIMENTS
4.4
DATA ANALYSIS AND DESIGN RECOMMENDATIONS
TASK 5.0
MATERIAL IMPROVEMENTS
5.1
Ga SUPPLIES AND COST PROJECTION
5.2
METAL ORGANIC PRODUCTION TECHNIQUE DEVELOPMENT
5.3
SAPPHIRE RIBBON PRODUCTION TECHNIQUE DEVELOPMENT
5.4
Ge SUPPLIES AND COST PROJECTION
5.5
EXPERIMENTAL EVALUATION OF SELECTED MATERIALS
TASK 6.0
MANUFACTURING PROCESSES
6.1
MANUFACTURING PROCESSES PRELIMINARY DESIGN AND PROJECTION
6.2
PRODUCTION EQUIPMENT PRELIMINARY DESIGN AND PROJECTION
6.3
PHYSICAL PLANT REQUIREMENTS PRELIMINARY PROJECTION
TASK 7.0
STUDY MANAGEMENT
BUSINESS MANAGEMENT
BRIEFINGS AND REVIEWS
DOCUMENTATION

*Figure A-2. Proposed Task Breakdown*

## A.3 NEED FOR PROPOSED INVESTIGATION

The system studies conducted by Rockwell[1] determined the general characteristics of an SPS configuration using GaAs solar arrays in place of Si. Study results indicated the potential of GaAs solar arrays to alleviate the severe weight/lifetime/efficiency/cost problems in the Si solar array concept. The solar collector array accounts for roughly 42 percent (GaAs) of the total SPS weight, and considering transportation costs, accounts for about 60 percent of the satellite system costs.

Table A-2 shows a system weight comparison between Si and GaAs solar cells. The impact on weight of radiation damage annealable assumptions are indicated for silicon. The table shows a potential weight penalty for silicon ranging between $22.2 \times 10^6$ kg and $36.82 \times 10^6$ kg.

The technical requirements that make the solar cell approach a competitive satellite system are very demanding. The present silicon approach uses cell efficiency of 17.3 percent AMO (28°C) based on assumed 15.8 percent achievable efficiency plus 10 percent for projected improvements utilizing a 2-mil solar

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[1] Satellite Power System (SPS) Concept Definition Study, NASA/MSFC contract NAS8-32475, Exhibits A/B, Final Reports (April 1978).

*Table A-2. Weight Comparisons - Point Designs*

| Parameter | Silicon | | GaAs |
|---|---|---|---|
| | Annealable | Non-Annealable | |
| Plan form | 71.45 km$^2$ | 95.2 km$^2$ | 81.63 km$^2$ |
| Required array power | 10.3 GW → | → | → |
| Solar cell area ($10^6$ m$^2$) | 60.75 | 83.16 | 30.6 |
| Reflector area ($10^6$ m$^2$) | - | - | 64.8 |
| Cell efficiency (28°C) | 17.3% | 17.3% | 20.0% |
| Radiation degradation factor | 0.96 | 0.70 | 0.96 |
| Collector array | | Weight ($10^6$ kg) | |
| Structure and mechanisms | 2.229 | 2.653 | 2.156 |
| Solar panels | 25.880 | 35.426 | 7.536 |
| Solar reflectors | - | - | 1.173 |
| Power distribution | 2.255 | 3.812 | 1.864 |
| Switch gear/controls | .579 | .682 | .407 |
| Attitude controls/IMS | .153 | .188 | .166 |
| | (31.096) | (42.761) | (13.302) |
| Antenna section | 16.297 | 16.297 | 16.297 |
| Subtotal | 47.393 | 59.058 | 29.599 |
| 25% growth | 11.848 | 14.765 | 7.399 |
| Total | 59.241 | 73.823 | 36.998 |

cell configuration at 0.427 kg/m$^2$. The highest output for thin silicon cells[1] is 78.5 mW/4 cm$^2$ ($\eta$ = 14.5% AMO, 28°C). The basic approach employed to achieve this high output includes use of shallow junctions and optimized grid patterns, back surface fields, texturized front surfaces, back surface reflectors, and higher resistivity (50 ohm-cm) silicon than is normal for space flight cells.

To achieve still higher efficiencies from silicon cells appears improbable, particularly for large-volume, low-cost requirements such as SPS. It is, therefore, prudent to examine alternatives to silicon. Gallium arsenide looks to be a most attractive solar cell for SPS. However, to be a viable candidate SPS cell and meet early technology verification requirements, GaAs cell development must begin at the earliest possible date.

The SPS program has established early technology verification requirements. These requirements are outlined in Figure A-3. Shown in the figure are some space flight system requirements in the 1987 to 1989 period. These systems provide technology verification when combined with ground test results.

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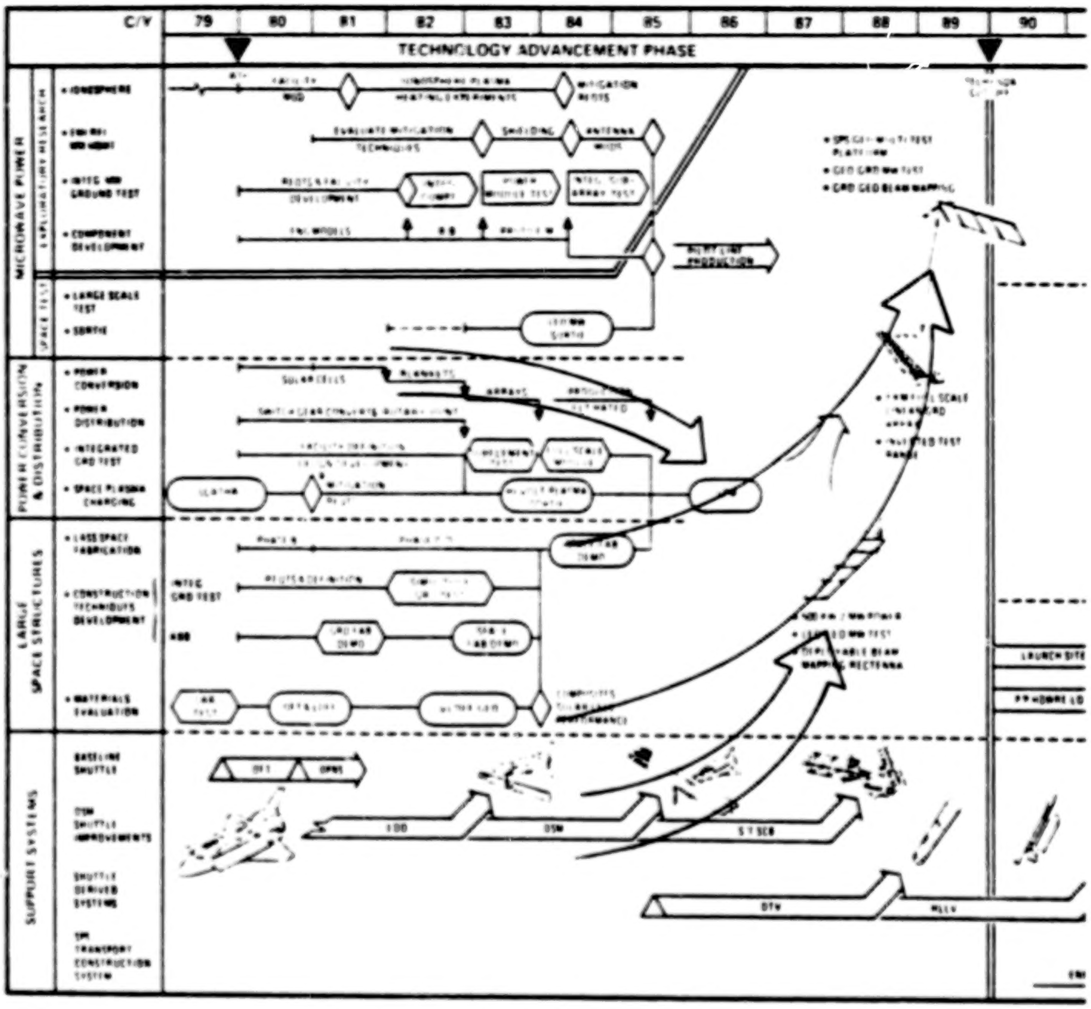
[1] Development of High Efficiency, Radiation Tolerant, Thin Silicon Solar Cells, Spectrolab, Inc., JPL Contract 954600, Final Report (October 1977).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TECHNOLOGY ADVANCEMENT PHASE
MICROWAVE POWER
EXPLORATORY RESEARCH
SPACE TEST
POWER CONVERSION & DISTRIBUTION
LARGE SPACE STRUCTURES
SUPPORT SYSTEMS
• IONOSPHERE
• INTEG GRD GROUND TEST
• COMPONENT DEVELOPMENT
• LARGE SCALE TEST
• SORTIE
• POWER CONVERSION
• POWER DISTRIBUTION
• INTEGRATED GRD TEST
• SPACE PLASMA CHARGING
• LARGE SPACE FABRICATION
• CONSTRUCTION TECHNIQUES DEVELOPMENT
• MATERIALS EVALUATION
BASELINE SHUTTLE
SHUTTLE IMPROVEMENTS
SHUTTLE DERIVED SYSTEMS
TRANSPORT CONSTRUCTION SYSTEM
SOLAR CELLS
ARRAYS
INTEG GRD TEST
COMPOSITES
OFT
OPNS
OTV
HLLV
LAUNCH SITE
PILOT LINE PRODUCTION

*Figure A-3. SPS Technology Advancement Plan*

A major item in this plan is the solar array. It will be necessary to demonstrate the technology readiness of the solar cells/arrays on some minimum size, probably ~100 kW (e.g., high efficiency ~20%, 125°C operating temperature, 0.252 kg/m$^2$ solar cell stack weight, 650 W/kg array output, 45.5 kV level, and concentration ratio of 2). It is mandatory that work toward these objectives start early with the solar cell development since fundamental technical and cost questions must be answered before proceeding further with the development and verification program. Questions of technical/cost are potentially SPS "show stoppers", and 1980 appears to be a key decision date in terms of NASA/DOE commitments for further SPS development work.

## A.4 SPECIFIC GOALS/PAYOFFS

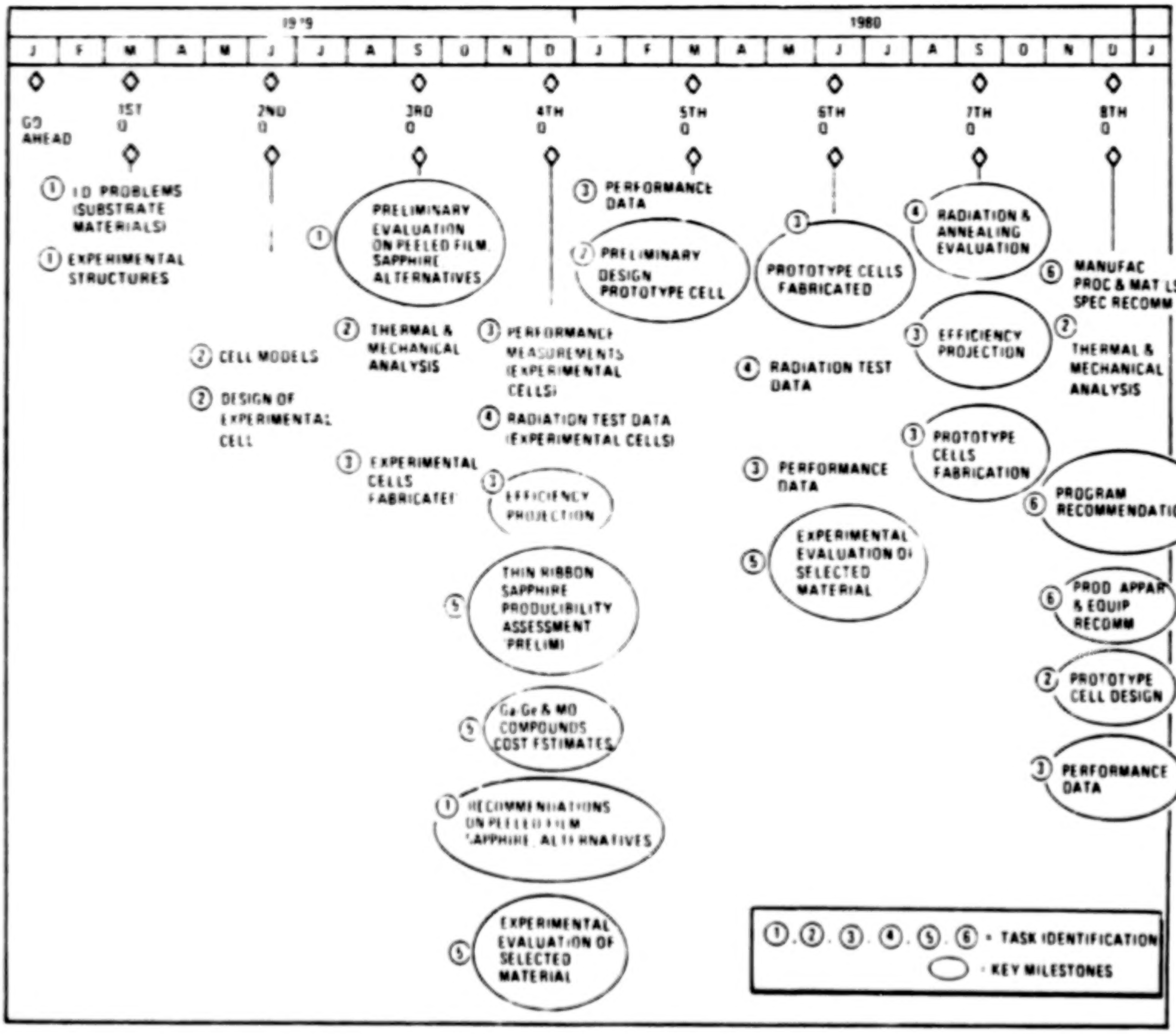
The specific goals of this proposed solar cell development program are:

1. To develop and evaluate a prototype GaAs thin-film solar cell designed to meet the early SPS technology verification requirements:
    - High efficiency
    - Low radiation degradation and/or annealable
    - Light weight
    - Compatible high-temperature operations (125°C) with concentrators (CR=2)
    - Low power degradation with high temperature (125°C)
    - Mass producible design
    - Potential low cost
2. To provide technical answers to assist NASA/MSFC in decision-making on GaAs solar cells for SPS. Specific concerns include:
    - Cell structure selection
    - Cell efficiency
    - Radiation allowables (annealability)
    - Material and process costs

NASA will benefit by this program with the development of a new space solar cell configuration which can meet many of the advanced space solar array technology requirements. The SPS program will benefit by being able to incorporate the characteristics of this solar cell into its solar array design and with an improved degree of certainty, plan the early technology verification program of the solar array. In addition, this solar cell technology may be advantageous to ground solar-photovoltaic systems.

The major program milestones are shown in Figure A-4. From Task 1 will come the recommendations on basic thin-film cell design. Substrate materials will be experimentally evaluated to determine the relative merits of sapphire, peeled film technology, gallium arsenide, and germanium substrate materials.

Task 1 activity will result in a recommendation on peeled film, sapphire, and alternatives by the end of the first year's effort. Cell modeling and performance analysis in Task 2 will lead to the design of experimental cells and result in the preliminary design of a prototype cell at the end of the first year. Thermal and mechanical analysis of the cell stack will be performed in this task. Task 3 will provide solar cell efficiency projections based on experimental cell test data during the first year and prototype cell data in the second year. Task 3 results in the prototype cell design and verification of performance values at the end of the two-year period.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4TH Q
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6TH Q
7TH Q
8TH Q
① ID PROBLEMS (SUBSTRATE MATERIALS)
① EXPERIMENTAL STRUCTURES
② CELL MODELS
② DESIGN OF EXPERIMENTAL CELL
① PRELIMINARY EVALUATION ON PEELED FILM SAPPHIRE ALTERNATIVES
② THERMAL & MECHANICAL ANALYSIS
③ EXPERIMENTAL CELLS FABRICATED
③ PERFORMANCE MEASUREMENTS (EXPERIMENTAL CELLS)
④ RADIATION TEST DATA (EXPERIMENTAL CELLS)
③ EFFICIENCY PROJECTION
⑤ THIN RIBBON SAPPHIRE PRODUCIBILITY ASSESSMENT PRELIM
⑤ GaGe & MO COMPOUNDS COST ESTIMATES
① RECOMMENDATIONS ON PEELED FILM SAPPHIRE ALTERNATIVES
⑤ EXPERIMENTAL EVALUATION OF SELECTED MATERIAL
③ PERFORMANCE DATA
② PRELIMINARY DESIGN PROTOTYPE CELL
③ PROTOTYPE CELLS FABRICATED
④ RADIATION TEST DATA
③ PERFORMANCE DATA
⑤ EXPERIMENTAL EVALUATION OF SELECTED MATERIAL
④ RADIATION & ANNEALING EVALUATION
③ EFFICIENCY PROJECTION
③ PROTOTYPE CELLS FABRICATION
⑥ MANUFAC PROC & MAT'LS SPEC RECOMM
② THERMAL & MECHANICAL ANALYSIS
⑥ PROGRAM RECOMMENDATION
⑥ PROD APPAR & EQUIP RECOMM
② PROTOTYPE CELL DESIGN
③ PERFORMANCE DATA
①, ②, ③, ④, ⑤, ⑥ = TASK IDENTIFICATION
= KEY MILESTONES

*Figure A-4. Proposed Program Milestones*

In Task 4 initial radiation test data would be provided on experimental cells during the first year. Major radiation test evaluations would be performed on prototype cells during the second year. An assessment of the technical credibility of self-annealing characteristics would be derived.

Task 5 would provide the answer to the technical and cost questions relating to producibility of thin sapphire ribbons, improved metal organic compounds and raw material cost of these components. Answers are provided on the bases of experimental evaluations by the end of the first year and improved materials will result during the second year. Task 6 provides manufacturing process concepts which are based on utilizing the prototype cell design.

## A.5 TECHNICAL OBJECTIVES AND PROGRAM RATIONALE

The overall technical objective of the proposed work is to investigate and develop one or more material combinations and processing technologies for fabrication of high-efficiency thin-film GaAs solar cells that meet the design and performance characteristics (efficiency, temperature stability, radiation resistance, and specific mass) required for the SPS solar array.

The goal of the program is sufficient valid technical data on the performance characteristics and probable fabrication techniques of the candidate cell configurations being investigated to permit firm recommendations to be made by the end of the second year regarding the suitability of thin-film single-crystal GaAs cells for future use in the SPS.

The rationale for the proposed program approach is that the unsurpassed photovoltaic properties of GaAs, its high optical absorption coefficient (requiring only very thin layers for maximum response), its relatively high-temperature operating characteristics, and the relatively high radiation-damage resistance and annealing properties of GaAs solar cells, combine to dictate that thin-film GaAs cell structures made by the MO-CVD process offer the best prospects of achieving the high performance and long life required for the SPS.

For firm and conclusive recommendations to be made with confidence regarding the expected performance and economic feasibility of thin-film single-crystal GaAs solar cells for the photovoltaic power conversion subsystem of the SPS, it is necessary that likely modifications or variations of the thin-film GaAs cell that are now known and appear to have the potential of fulfilling the SPS performance and cost requirements be considered, and either be eliminated from experimental evaluation in the proposed program because of identifiable shortcomings or be included in the work and evaluated during the course of the study. It is not sufficient to investigate only a single configuration of the cell or a single process or method for making the cell at this time. Thus although the Rockwell SPS design concept includes the GaAlAs/GaAs single-crystal thin-film solar cell grown by the metalorganic chemical vapor deposition process on a substrate of thin single-crystal sapphire ribbon, several variations of cell configuration, substrate material and form, active photovoltaic barrier type and location, and cell fabrication processing are included in the proposed investigations.

Because of the eventual enormous production requirement and stringent weight/performance requirements of SPS, the GaAs solar cells developed in this program will be fabricated by metalorganic chemical vapor deposition. This process allows the consideration of two thin-film GaAs solar cell structures that can be fabricated only by MO-CVD. As a result, new options for lightweight, high-efficiency solar cells with radiation resistance will be available.

The development of these structures involves some risk but the potential payoff for efficient energy conversion as a result of the proposed program appears very large.

To achieve the overall program objective within this material, the following specific technical objectives will guide the conduct of the proposed program:

- Demonstrate and develop the technology for fabricating high-efficiency GaAs solar cells on single-crystal sapphire substrates in both the conventional and inverted configurations.
- Demonstrate and develop the technology for fabricating high-efficiency thin-film GaAs solar cells on reusable or disposable substrates.
- Explore and demonstrate the feasibility of fabricating high-efficiency GaAs solar cells on thin Ge substrates and assess the economic viability of this combination.
- Develop and apply rigorous analytical modeling techniques for predicting the performance of GaAs thin-film cells in the configurations to be explored and devise optimum device designs based on this modeling.
- Determine the tolerance of the various solar cell structures to irradiation by charged particles and the feasibility of low-temperature annealing to remove whatever radiation damage does occur.
- Utilize subcontracts to develop and improve feedstock materials for proposed cell fabrication processes and cell structures.

## A.6 PROPOSED TECHNICAL APPROACH

The proposed multi-faceted program will provide data that will permit firm recommendations to be made by the end of 1980 regarding the suitability of thin-film single-crystal GaAs solar cells for future use in the SPS. The proposed program schedule is shown in Figure A-5.

The program is intended to provide the necessary factual data and--where complete data may be locking--the inferred evidence, based on trends of partial data combined with applicable physical principles and known behavior patterns of electronic materials and devices, to permit conclusive recommendations to be made by NASA on the expected performance and economic feasibility of thin-film single-crystal GaAs solar cells for the photovoltaic power conversion subsystem of the SPS, taking account of the scheduling requirements of the SPS project.

For such recommendations to be made with confidence it is necessary to consider likely modifications or variations of the thin-film GaAs cell that are now visible and appear to have the potential of fulfilling the SPS performance and cost requirements. These then must be either eliminated from experimental evaluation in the proposed program because of identifiable shortcomings or be included in the work and evaluated during the course of the study. It is not sufficient to investigate only a single configuration of the cell or a single process or method for making the cell unless a sufficiently strong *a priori* case for such action can be made on the basis of present data and experience, and it is believed that such a case cannot be made at this time.

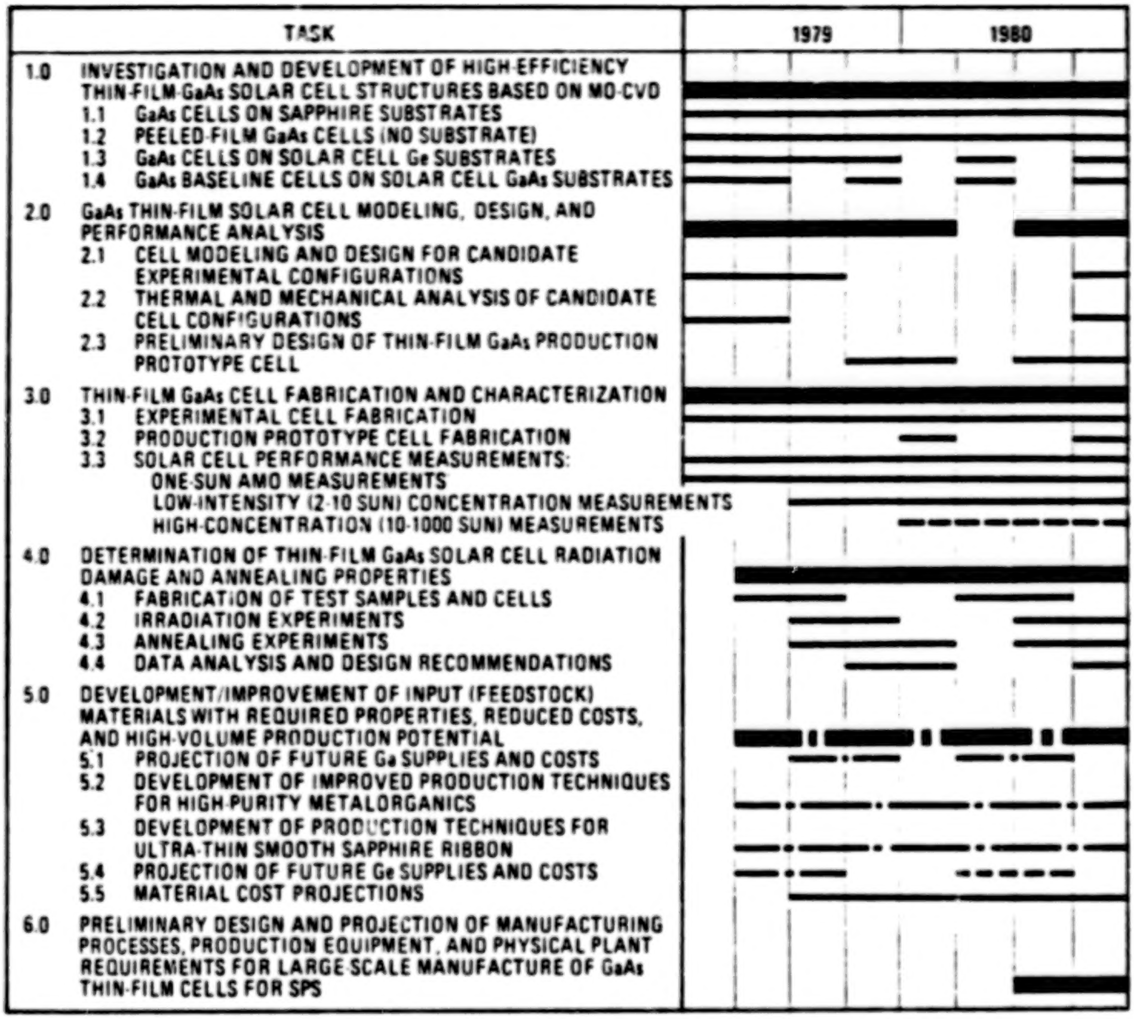


*Figure A-5. Program Schedule*

Thus, although the reference SPS design concept includes the GaAlAs/GaAs single-crystal thin-film solar cell grown by the metalorganic chemical vapor deposition (MO-CVD) process on a substrate of thin single-crystal sapphire ribbon, several variations of cell configuration, substrate material and form, active photovoltaic barrier type and location, and cell fabrication processing are included in the proposed investigations.

Cell configurations to be included are (1) thin-window heteroface structures, (2) shallow-junction homogeneous cells, (3) heterojunction cells, and (4) Schottky-barrier cells. Substrate materials to be evaluated include (1) that of the Rockwell point-design concept, single-crystal sapphire ribbon, in both inverted and conventional cell structures; (2) single-crystal Ge in three different forms; (3) several different compound or alloy semiconductors, primarily as deposited films on other crystal wafers (or ribbons) of semiconductor or high-temperature oxide materials; (4) certain metals in the form of films grown on single-crystal substrates; and (5) single-crystal GaAs wafers and films, mainly to provide "conventional" single-crystal thin-film GaAs cells for baseline-reference performance data. Cell growth and fabrication processing involving both permanent substrates and reusable substrates (so-called "peeled-film technology") and either all-front contact or two-sided contact technology will be investigated.

Only the GaAs materials system is to be investigated in the proposed work, on the basis of its being clearly the front-running candidate among presently known photovoltaic materials and the one most susceptible to further significant improvements through application of proven materials technology. Further, for reasons regarded as equally compelling, the MO-CVD film-growth process is the only one to be included in the program. This has been determined in view of the eventual production requirements for the SPS and the established quality of the materials and solar cells produced by this method to date.

The program emphasis in the first year is on the fundamental exploratory investigations of Task 1, in which the various thin-film GaAs cell structures formed by the MO-CVD process will be prepared using several variations in configuration, substrate, and procedure. In the second year the effort on Task 1 will be reduced somewhat, the intention being that the results of the first year's work will permit a reduction in the variety of alternatives still requiring evaluation and development, so that the surviving options can be further examined and the more promising selected for continued development and investigation to the end of the program. Simultaneously, in the second year the emphasis on the other tasks--experimental cell fabrication and evaluation (Task 3), radiation testing (Task 4), and preliminary design and projection of probable manufacturing processes, specification of materials, design of production apparatus and equipment, and specification of facilities and physical plant requirements (Task 6)--will increase as the most likely version of the thin-film GaAs cell becomes more evident.

## A.7 BASIS FOR SELECTION OF THIN-FILM SINGLE-CRYSTAL GaAs AS CELL MATERIAL FOR SPS

The unsurpassed photovoltaic properties of GaAs, its high optical absorption coefficient (requiring only very thin layers for maximum response), its relatively high-temperature operating characteristics, and the relatively high radiation-damage resistance and annealing properties of GaAs solar cells combine to dictate that thin-film GaAs cell structures made by the MO-CVD process be considered the best prospects of achieving the high performance and long life required for the SPS.

The choice of thin-film, single-crystal GaAs as the basic material for fabrication of the solar cells for the photovoltaic power conversion subsystem of the Rockwell SPS design is based on (1) the superior intrinsic photovoltaic properties of GaAs under solar illumination; (2) the thermal stability of the material at relatively high operating temperatures; (3) its relatively high resistance to damage by electron and proton irradiation and its apparent damage-recovery (annealing) characteristics at moderately elevated temperatures; and (4) the fact that it can be grown with very high quality by deposition techniques that are adaptable to scaled-up, large-volume production, as will be needed for the SPS project.

Prior to the dramatically increased activity on photovoltaic solar cell materials and devices within the past three years, the majority of research and engineering development effort in this field had gone into achieving improvements in the single-crystal Si solar cell and into improving fabrication processes for thin-film CdS solar cells and, to a much smaller degree, preparing experimental cells of single-crystal GaAs and a few other compound semiconductors. The Si cell, of course, became the industry standard and has received by far the greatest amount of engineering and production effort. Arrays of Si cells have supplied reliable power for most of the space vehicles and satellites launched throughout the world in various space programs over the past 15 years.

However, theoretical considerations show that various compound semiconductors - especially GaAs and its related alloys - should provide significantly higher conversion efficiencies than are available with Si cells. Although pilot-line quantities of single-crystal GaAs cells were fabricated several years ago, the performance of experimental arrays in actual space missions was generally disappointing.

Work in the past several years with composite cells involving GaAs and a front layer of another material as a "window" has, however, renewed interest in the significant advantages of GaAs as a solar cell material; these advantages include the following characteristics:

1. The bandgap energy (~1.4 eV) is a better match to the solar spectrum; higher theoretical efficiencies (well in excess of 20 percent) than for Si are thus to be expected.

2. The decrease of power output with increasing temperature for GaAs is about half of that for Si cells, because of the larger bandgap that allows higher temperature operation of the junction.

3. GaAs cells typically have lower minority carrier lifetimes and diffusion lengths than Si cells, and so are less susceptible to radiation damage.

4. The larger bandgap of GaAs results in higher output voltage per cell than for Si, although the current per cell is smaller.

5. The optical absorption edge in GaAs is quite steep (it is a direct-bandgap semiconductor) so that most solar radiation is absorbed very near the surface, eliminating the need for thick cells to capture most of the incident energy. This characteristic also reduces the susceptibility to radiation damage because of the smaller volume (i.e., thickness) of material for absorbing (stopping) charged particles.

There are some disadvantages of GaAs relative to Si, one of which is related to item 5 above. Because of the absorption and generation of charge pairs so close to the surface, the high surface recombination velocity that is also characteristic of GaAs (10 to 100 times that found in Si) results in reduced minority carrier collection efficiencies in junction-type devices, due to surface recombination losses. Additionally, since the minority carrier diffusion lengths in GaAs are typically small compared with those found in single-crystal Si, very thin (<0.5μm) layers with extensive electroding (grids) are required on the illuminated side of the junction to reduce cell series resistance as much as possible. Even with these measures, the losses at the front of a simple cell have been found to be too high for acceptable cell operation under normal conditions.

This problem was the principal motivation for development of the window-type cell, in which a layer of another semiconductor is applied to the illuminated surface of the GaAs to remove the active junction region sufficiently far from the incident-light surface to reduce recombination losses, and at the same time add conductive material that reduces the series resistance of the cell. The window material must provide an interface with the GaAs that is sufficiently good structurally for the interface itself not to become a source of recombination losses. Additionally, the bandgap of the window material must be large enough that there are no significant losses of the incident solar radiation due to absorption in the window material (unless other aspects of the design allow the carriers generated by such absorption to be collected by the active junction). There are also other methods, primarily related to the particular cell design configuration employed, that can circumvent this surface-recombination-loss problem in GaAs cells. Although it is a factor in specific cell design, this property of GaAs has been found not to prevent the achievement of superior cell performance.

The fact that thin-film single-crystal GaAs solar cells essentially equivalent in performance to the highest efficiency cells of this material made by any other method to date have also been made by the MO-CVD process and the fact that the MO-CVD process lends itself to scale-up to large-volume production probably better than any other contemporary thin-film semiconductor deposition technique together constitute one of the strongest arguments favoring selection of this combination of material, configuration, and process for the SPS solar cell. Characteristics of the MO-CVD process clearly indicate a good probability of successful scale-up to the long-term requirements of the SPS project.

The large absorption coefficient of GaAs in the wavelength region to the high-energy side of its fundamental absorption edge is such that most (i.e., 90 percent or more) of the available radiation in the solar spectrum is absorbed within a thickness of 2μm or less. A thickness in excess of 100μm of Si is required for similar absorption. The fact that GaAs is a direct-bandgap material and Si an indirect-bandgap semiconductor means that the transition from non-absorbing to absorbing is much more abrupt for GaAs than for Si in progressing from long wavelengths to shorter wavelengths, past the band edge.

The difference in bandgap energy for these two semiconductors means that GaAs responds only to that portion of the total solar spectrum that is to the short-wavelength side of ~0.9μm, while Si responds to all photons of the short-wavelength side of ~1.1μm. Although there is a significant amount of solar energy in the band between these two wavelengths, the net result of all factors that bear on photovoltaic conversion efficiency is that the theoretical values for GaAs are significantly higher than for Si, as indicated earlier.

The strong absorption properties of GaAs throughout most of the width of the wavelength band between the GaAs band edge and the short-wavelength limit of the AMO solar spectrum permit the successful use of thin deposited films of GaAs for high-efficiency solar cells, whereas either bulk crystals or very thick films (50-100μm) of indirect gap materials such as Si are required for adequate absorption of a sufficient amount of the incident solar radiation to even approach maximum performance for those materials. This fact alone favors GaAs over Si for the SPS application by a considerable margin.

The resulting advantages of GaAs over Si thus also relate to the reduced weight and consequent lower cost of a smaller amount of the active semiconductor material. Cost comparisons of these two candidate cell materials must be made with care. Major differences exist in the nature and maturity of present technologies in the two cases for the three principal cost categories associated with solar cell array fabrication: (1) processed or purified input material; (2) fabrication of large-area films (or "sheets", which can be in the form of flat polished or etched wafers); and (3) cell and array fabrication.

High-purity, semiconductor-grade polycrystalline Si now costs about $60 per kg; it is prepared by a series of processes that are highly developed and uses input materials almost unlimited in abundance; Si itself is the second-most abundant of all the elements. Single-crystal ingots of Si, grown by the Czochralski method and with properties adequate for use in fabricating single-crystal wafer-type solar cells of the conventional kind, cost about $0.25 per g for moderate quantities.

GaAs, on the other hand, is prepared almost exclusively as an ultrapure, single-crystal, semiconductor compound, either in bulk ingot form by Czochralski or Bridgman crystal growing techniques or in single-crystal layer form by liquid phase epitaxy (LPE) or chemical vapor deposition (CVD) techniques. Although these processes are now highly developed, they are by no means developed on a large production scale. Single-crystal GaAs prepared by the Bridgman technique now costs about $7 per g in bulk ingot form, while ultra-high purity Ga metal and As metal separately cost about $0.75 and $0.65 per g, respectively, in small quantities. The world supply of Ga (roughly half the weight content of GaAs) is known to be limited, although there appears to be little need for concern about As abundance.

Because of the variation in the amount (i.e., number of grams) of photovoltaic material required for various configurations of solar cells of a given solar conversion efficiency, caused by differences in optical properties from material to material or by variations in the amount of the material required (for structural integrity or other reasons) among different physical configurations of a given semiconductor, it is necessary to examine comparative materials costs on a unit area basis.

When such a calculation is made for Si on a square meter ($m^2$) basis for both the present cost of semiconductor-grade polycrystalline material (~$60 per kg), used as the input material for fabricating single-crystal high-efficiency Si solar cells (including those in ribbon or dendritic web configuration), and the projected 1986 DOE/JPL Low-cost Solar Array Project cost goal of \$10 per kg for so-called "solar cell grade" material, the cost per $m^2$ vs Si thickness curves shown in Figure A-6 are obtained. The input material cost associated with a 6µm layer of Si is \$0.84 per $m^2$ in terms of present prices and \$0.14 per $m^2$ in terms of the 1986 cost goals. A 100µm layer - a more realistic thickness for an Si solar cell - corresponds to a material cost of \$13.98 per $m^2$ at present prices and \$2.33 per $m^2$ at \$10 per kg, while the costs for a 200µm (8 mil) thickness are \$27.96 and \$4.66 per $m^2$, respectively.

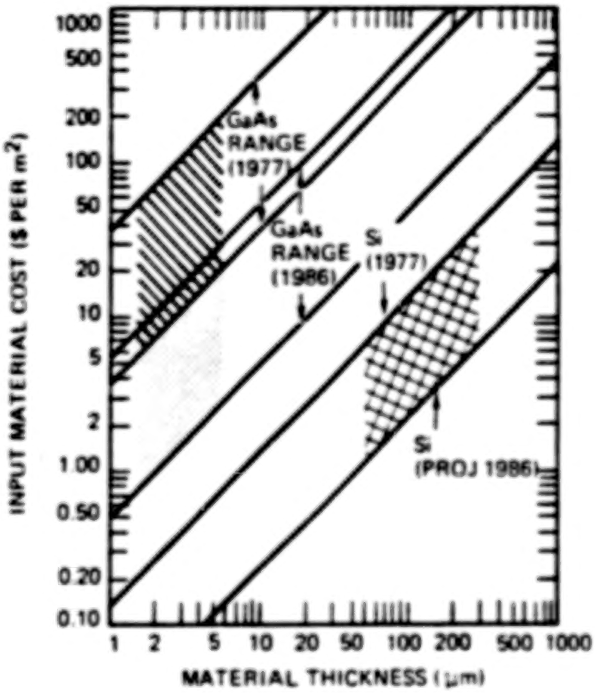


*Figure A-6. Comparison of Present and Projected Input Material Cost*

It is difficult to identify corresponding costs for GaAs because of significant differences in the input materials and in processing and fabrication techniques. However, it is possible to designate a GaAs input materials cost range, somewhere within which must fit the figure for GaAs that corresponds to the \$0.06 per g present cost for semiconductor-grade polycrystalline Si. The upper limit of this range may be taken as the ~\$7 per g present cost of high-quality, single-crystal GaAs ingot material; and the lower limit may be considered to be the combined cost of 0.48 g of ultra-high-purity Ga metal and 0.52 g of ultra-high-purity As metal (the proportion in which they occur in GaAs) at their present separate costs, or ~\$0.70 per g - an order of magnitude smaller than the upper limit. This range is from one to two orders of magnitude larger than the present cost per unit weight of semiconductor-grade polycrystalline Si. This difference in cost per unit weight is not surprising in view of the vast differences in technology development, applications history, present market volume, and material abundance in the two cases.

If it is assumed that the same diligence in technical development and the same large-market motivation that are expected to exist for Si cell material technology will also prevail in GaAs cell material technology in this same time period (to 1986), then it may also be reasonable to project a similar factor reduction in GaAs input material costs by 1986 - say to a range from \$0.10 to \$1.00 per g. The lower end of this suggested range is not greatly different from the present actual cost per gram (\$0.06) of semiconductor-grade ploycrystalline Si. These two "constructed" cost ranges for GaAs material have been converted to costs per $m^2$ for the same semiconductor thickness range as used above for Si and are also shown in Figure A-6. Note that because of the density difference (2.33 $g/cm^3$ for Si and 5.32 $g/cm^3$ for GaAs), a given thickness of GaAs is ~2.3 times heavier than the same thickness of Si.

As shown in the figure, a 6μm layer of GaAs has an associated input material cost from \$22.34 to \$223.44 per $m^2$ in terms of the present price range identified above,and from \$3.19 to \$31.92 per $m^2$ in terms of suggested 1986 cost goals. Similarly, the figures for a 100μm thickness are \$372.40 to \$3724 per $m^2$ for present prices and \$53.20 to \$532 per $m^2$ at the projected 1986 level.

When the important allowance is made for the difference in optical absorption properties of Si and GaAs in the region of the solar spectrum, some of the apparent material cost discrepancy between Si and GaAs is greatly reduced. Calculation of an idealized short-circuit current for Si and GaAs cells, based on assumptions of single-pass illumination and transmittance normal to the front face, unity quantum efficiency, and perfect charge collection efficiency, shows that very little additional cell response results for GaAs thickness over ~6μm, while significant additions to response continue in Si for thicknesses up to 300μm.

The significance of these differences is illustrated in the figure, in which the approximate thickness regions for Si and GaAs that should be addressed in comparing materials costs are shown as shaded areas. What this figure shows is that for the amount of the semiconductor actually required for the active region of a solar cell of comparable properties in the two cases, there is far less than the usually considered material cost difference per unit area of cell, even in terms of current prices. It further shows that if GaAs were subjected to the same kind of input material cost reduction effort as is planned for Si over the next 8 to 10 years, then input material costs for the required amount of active semiconductor could actually be quite similar in the two cases.

Although the GaAs cell itself--whatever specific configuration is involved--is believed to offer the highest ultimate AMO conversion efficiency of all of the single-component photovoltaic cells developed to the present time, based both on theoretical analyses of the photovoltaic effect at potential barriers in semiconductor materials and on the present state of development of the respective material technologies, it is essential for a long-term project of the magnitude and importance of the SPS to be planned so that future technology developments having significant positive impact on its performance and/or cost can be incorporated with minimum delay and technological complication. For the photovoltaic power conversion subsystem, the efficiency under orbital operating conditions of the basic solar cell unit used in forming the solar array is a critical performance parameter that in turn affects essentially all other design aspects of the SPS. For every increase in the cell percentage operating efficiency by as much as 1 (e.g., from 20 to 21 percent), a major reduction in SPS area, weight, complexity, and cost will result. This factor is one of the several principal reasons for the selection of the GaAs single-crystal cell over the Si single-crystal cell in Rockwell's SPS design, for example.

The prospect of a dramatic increase in cell operating efficiency, even with respect to the present high value of ~20 percent (AM0, 28°C) achieved in the best single-crystal GaAs cells, is offered by the concept of the tandem, multiple-bandgap solar cell. Theoretical analyses by various investigators have shown that the maximum conversion efficiency for the solar spectrum that can be expected from any one p-n junction type of photovoltaic cell operating at its maximum power point (at ~25°C) is in the 20 to 25 percent range, the specific theoretical maximum depending primarily upon the bandgap energy $E_g$ of the particular semiconductor involved. Analyses of the projected performance of Si and GaAs solar cells under AM0 illumination indicate expected maximum solar conversion efficiencies of about 20 to 21 percent for Si and perhaps up to 22 to 24 percent for GaAs, with all controllable parameters optimized.

Whereas the use of sunlight concentration offers one method of achieving increased electrical power output per unit area of solar cell surface, another approach to more efficient use of the solar spectrum is based on the fact that a photovoltaic cell has two major obvious limitations on its ability to convert the incident solar photons, each of energy hν, into hole-electron pairs that can subsequently be separated, collected, and delivered to an external load. The first is that only those absorbed photons of energy greater than the bandgap energy $E_g$ can produce band-to-band excitation in the semiconductor and thus charge separation and possible delivery to the load. The second is that excess bandgap energy $E_g$--that is, all of the energy beyond that required to produce a single hole-electron pair--is dissipated internally as heat in the device.

The most efficient response of p-n junction cell is to photons of energy just exceeding the bandgap energy, so if two or more solar cells of differing bandgap energy (and thus of different composition) could be arranged appropriately to "share" the solar spectrum, with each operating on that portion of the spectrum to which it is most responsive, a combination converter of overall power efficiency exceeding that of the individual cells used separately in the full solar spectrum could quite possibly be realized. This concept is not new, having been first proposed in 1955 and examined by various workers at intervals since that time.

There are two principal embodiments of this concept. One involves interposing dichroic mirrors or filters (i.e., "beam splitters") in the incident beam of solar radiation so that selected radiation of a portion of the spectrum is diverted to a solar cell whose properties (mainly bandgap energy ($E_{g1}$) allow it to make relatively efficient use of that selected band of radiation, while allowing the remainder of the spectrum to pass on to a second filter/mirror, which again selects a portion of the spectrum to direct onto a second cell of bandgap energy $E_{g2}$, while transmitting the remainder to a third cell (or a third filter/mirror), and so on. The availability of beam-splitting, filter/mirror materials that can be tailored to this type of segmenting in such a way as to direct bands of the spectrum to cells that are designed (primarily through selection of the composition of the semiconductor) to be efficiently responsive to the photon energies involved makes this version of the multiple-cell concept attractive for concentrator systems where the cost of the complexity and size of the composite converter itself will not be a controlling economic or logistic factor.

The other modification of the multiple-cell concept--and the one with potential major impact on the SPS--can now be seriously considered for practical applications primarily because of the remarkable progress made in thin-film photovoltaic material technologies in the past several years. This version involves two or more solar cells of differing composition (and thus differing bandgap energies) used optically in series, in a tandem or stacked arrangement. The cell of largest bandgap energy $E_{g1}$ receives the full solar spectrum incident on its front surface, converting what it can of the absorbed photons of energy greater than $E_{g1}$ and transmitting the radiation of energy $<E_{g1}$ on to the second cell, of bandgap $E_{g2}$, which utilizes the narrowed band of energies to generate photovoltage and photocurrent consistent with its photovoltaic properties and transmits the remaining radiation of energy $<E_{g2}$ on to a third cell, if used, and so on. This configuration of the tandem or stacked multiple-bandgap solar cell is shown schematically in Figure A-7.

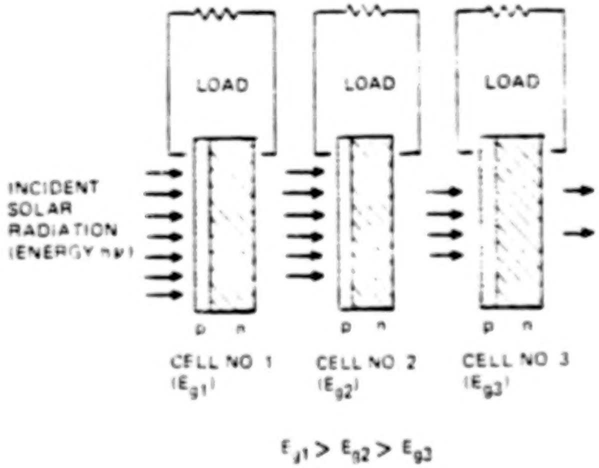


*Figure A-7. Schematic Representation of Stacked Multiple-Bandgap Solar Cell*

Although simple in concept, the stacked multiple-bandgap solar cell (SMBSC) involves difficult material problems and design and fabrication complexities. A major problem to be solved is the question of the design of the interface between the back side of the first component and the front side (incident light) of the cell next in line in the stack. Should the electrical contact be made simply a series connection, with the current leaving the first cell entering the second cell directly (conceptually the simplest structure, and shown in Figure A-8) or should the photon-generated current of each cell be extracted separately? In the first instance it becomes necessary to match photocurrents of the two adjoining cells at their operating points (not the short-circuit currents), and this requirement alone is accompanied by major difficulties of both material selection and interface design. However, this arrangement is by far the more attractive, since it makes maximum use of the compactness and fabrication advantages of monolithic thin-film semiconductor technologies.

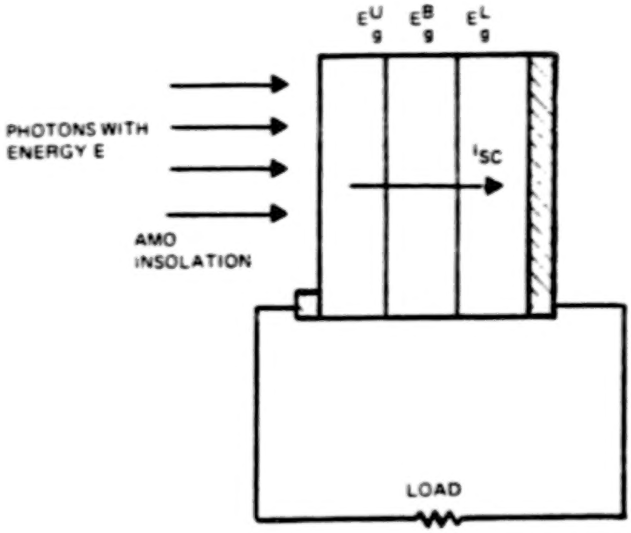


*Figure A-8. Schematic Representation of SMBSC Configuration Involving Both Electrical Optical Series Arrangement*

Over-simplified theoretical models of SMBSC configurations can give rise to a variety of possible cell combinations (or, more correctly, possible combinations of bandgap energies) that appear to offer very attractive combined conversion efficiencies--some approaching the probable theoretical upper limit of 40 to 50 percent for solar conversion efficiency for a semiconductor-based converter system having no loss of the excess photon energy.

More accurate models of such configurations, however, result in relatively few combinations of either two- or three-cell systems that meet design requirements yet represent material composities that are compatible and fabricatable by presently known technologies. The complexity of systems involving four (or more) component cells goes up rapidly, as does the difficulty of successfully fabricating the system even on an experimental laboratory basis.

Preliminary modeling of SMBSC assemblies of the type shown in Figure A-8 has recently been carried out at Rockwell as part of an experimental research and development contract program being undertaken jointly by ERC and the Science Center for the Air Force Aero Propulsion Laboratory. The objective of this program is the development of a technology to fabricate solar cell assemblies with greater than 25 percent conversion efficiency at 25°C under one-sun intensity in space sunlight (AMO, ~/35 mW/cm$^2$) illumination, with delivery of 100 2×2 cm SMBSC assemblies scheduled at the conclusion of the 24-month program.

Table A-3 shows a summary of the results of the preliminary modeling using the basic principles that must be applied to the SBMSC concept. The various materials considerations and photovoltaic device design factors that must be applied in selecting possible combinations for a practical SMBSC are quite complex, but the net result is indicated in the table. Individual cells that compose the two-cell, three-cell, or four-cell stacks are identified by the bandgap energy of the active cell material. The 1.42 eV cell involved in each of the combinations listed is the GaAs cell, and this point is of special significance to be discussed below.

*Table A-3. Calculated Ideal and Expected AMO Efficiencies for SMBSC Combinations with Two, Three, or Four Cells*

| | Efficiency (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Two Cells | | | | Three Cells | | Four Cells | |
| Bandgap Energy | Ideal $\eta$ | Expected $\eta$ | Ideal $\eta$ | Expected $\eta$ | Ideal $\eta$ | Expected $\eta$ | Ideal $\eta$ | Expected $\eta$ |
| 2.0 eV | | | 20.0 | 14.9 | 20.0 | 14.9 | 20.0 | 14.9 |
| 1.42 eV (GaAs) | 26.4 | 19.8 | 13.0 | 9.7 | 13.0 | 9.7 | 13.0 | 9.7 |
| 1.0 eV | | | | | 7.8 | 5.6 | 7.8 | 5.6 |
| 0.8 eV | 7.5 | 4.9 | | | | | 3.5 | 2.3 |
| Combined $\eta$ Total | 33.9 | 24.7 | 33.0 | 24.6 | 40.8 | 30.2 | 44.8 | 32.5 |

The table gives both theoretical conversion efficiencies for the various combinations, based on idealized junction characteristics and no current collection losses, and realistic projections of efficiencies that could be expected in practical assemblies after adequate development of the particular structures involved, based on empirical data obtained with experimental high-efficiency thin-film GaAs solar cells. The possibility of achieving efficiencies of over 25 percent--possibly greater than 30 percent--is evident from these data, provided the required materials and device technology problems can be adequately solved.

The Air Force contract program cited above is intended to attack those problems, utilizing both MO-CVD and liquid phase epitaxy (LPE) thin-film growth techniques at Rockwell. Upon consideration of the properties of candidate photovoltaic materials, the available substrate materials, contact materials and interface problems, and the present maturity and anticipated growth of the various material technologies, the GaAlAs/GaAs material systems were selected as the basic building block for development of the SMBSC. This material system is now highly developed at Rockwell, both with MO-CVD technology and LPE technology. The MO-CVD process, in particular, is adaptable to large-scale, large-area device production even for structures as complicated as the SMBSC.

Thus, with the GaAs solar cell as a component cell common to each of several different SMBSC structures,as indicated in Table A-3, and with several of these structures to be investigated and developed over the next several years by the MO-CVD process, the implications for the SPS reference design that also involves the thin-film GaAs solar cell are evident. If the SMBSC investigations lead to thin-film cell efficiencies in excess of the present cell design efficiencies used for the reference SPS concept, then at an appropriate time in the development of the SPS conversion subsystem, it should be possible to incorporate the closely related SMBSC, based on GaAs and produced by the MO-CVD process, into the SPS with minimum perturbation to the project schedule and maximum benefit to the SPS performance.

This opportunity constitutes a strong additional advantage for selection of the thin-film GaAs cell for the SPS. It also is another advantage of using the MO-CVD process technology for production of this GaAs solar cell, beyond those specific to the process itself.

# APPENDIX B

# POWER DISTRIBUTION TECHNOLOGY ADVANCEMENT

The power distribution subsystem is identified as a key technology issue area due to the potential impact of dc/dc converter and switchgear projected weight on the overall SPS system mass.

Figure B-1 shows a simplified SPS power distribution system for the solar photovoltaic three trough end-mounted antenna concept. The distribution system consists of the solar array interties, main feeders, switchgears, summing busses, tie busses, sliprings, regulators, high and low dc-dc converters, battery charging system, array subsystem bus, and subsystem cabling. The interties transfers the power from the solar array to the main feeders. The on-board data processing system performs the required switching of the submodules to maintain the bus regulation as required for the satellite power system. The power from the main feeders is transferred to a split summing bus via switchgear. Tie busses then connect the summing busses to the sliprings. A split summing bus and two sets of sliprings gives redundancy on the antenna in case of a partial power failure on the array. Individual klystron dc voltage conversion is performed by centralized converters (one for each brush assembly). A battery and battery charging system is for partial power to keep the klystrons warm and required housekeeping tasks during the eclipse periods.

## B.1 CURRENT DC/DC CONVERTER TECHNOLOGY PROJECTIONS

Over 20 companies involved in dc/dc converter and switchgear development were contacted for technology regarding current and future development endeavors each may be involved with for extending the present day's state of art for high dc voltage for dc to dc converters and switchgear. Problems and possible solutions were discussed with each company contacted.

Data on eight systems are shown in Figure B-2 from a review of current technology in dc/dc converters. These systems are referenced to the numbers on the graph, and are:

① 37 watt, dc/dc converter, stripped down, unable to operate in a stand alone mode

② 250 watt, dc/dc converter, 20-80 volt dc input

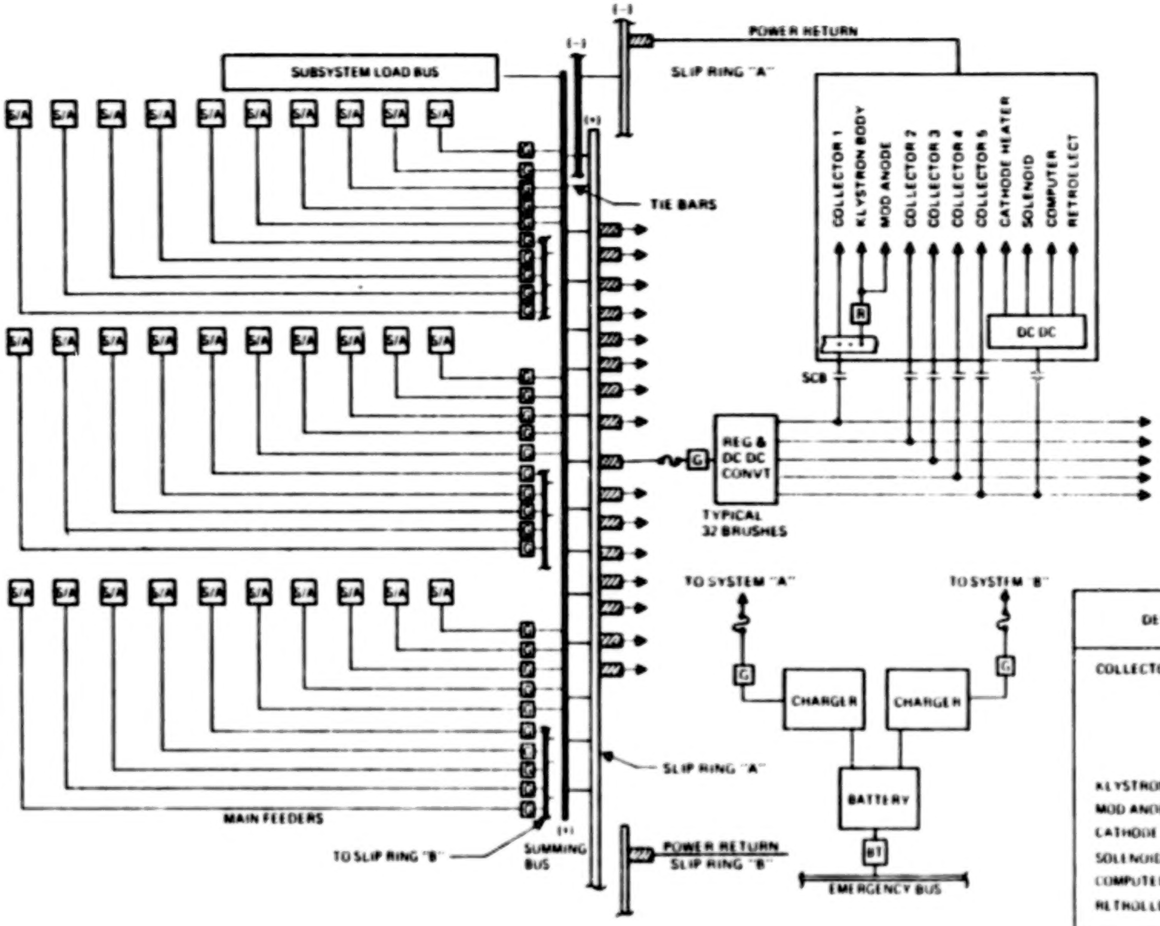
③ 1200 watt, dc/dc converter, 28 volt dc input

④ 1500 watt, inverter operating at 20 kHz

⑤ 2400 watt, dc/dc converter, 28 volt dc input

⑥ 25 kW, extrapolation of TRW unit from ⑤

B-2


(–)
POWER RETURN
(–)
SUBSYSTEM LOAD BUS
SLIP RING "A"
S/A
G
(+)
TIE BARS
COLLECTOR 1
KLYSTRON BODY
MOD ANODE
COLLECTOR 2
COLLECTOR 3
COLLECTOR 4
COLLECTOR 5
CATHODE HEATER
SOLENOID
COMPUTER
RETROELECT
R
DC DC
SCB
REG & DC DC CONVT
TYPICAL 32 BRUSHES
TO SYSTEM "A"
TO SYSTEM "B"
CHARGER
CHARGER
BATTERY
BT
EMERGENCY BUS
SLIP RING "A"
MAIN FEEDERS
TO SLIP RING "B"
SUMMING BUS
(+)
POWER RETURN
SLIP RING "B"

| | |
|---|---|
| S/A | SOLAR ARRAY |
| G | SWITCH GEAR |
| SCB | SOLID STATE CRK BRKR |
| R | REGULATOR |
| BT | BATTERY TIE CONTACTOR |

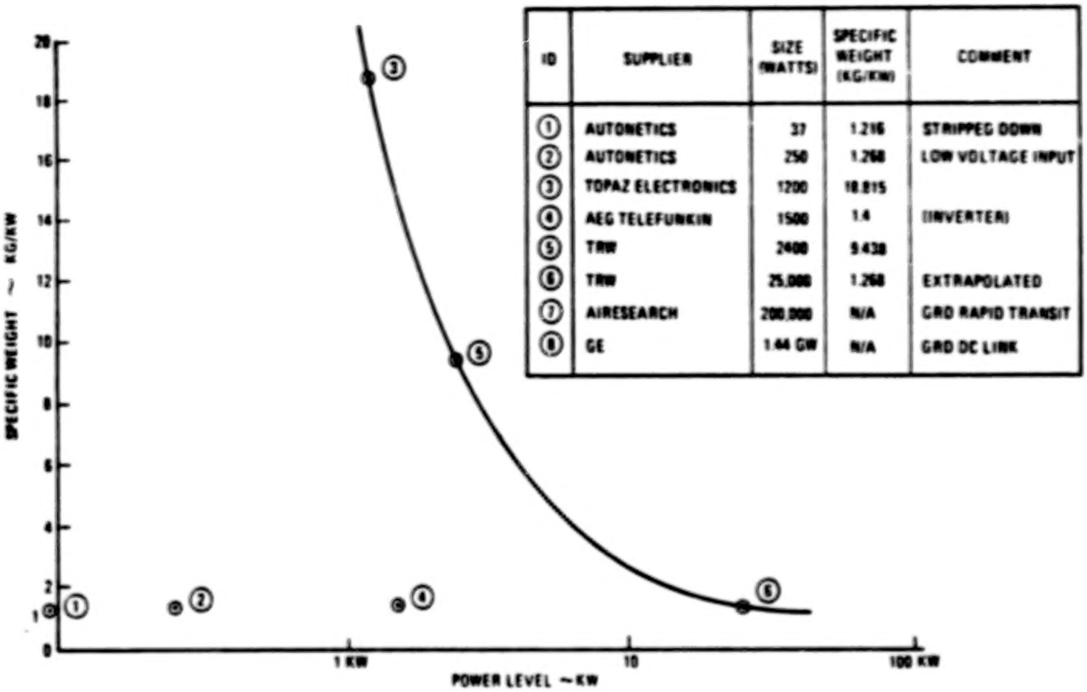
KLYSTRON REQUIREMENTS

| DEVICE | VOLTAGE | POWER KW | REGULATION |
|---|---|---|---|
| COLLECTOR 1 | 40 KV | 11.2 | |
| 2 | 32 KV | 11.2 | |
| 3 | 24 KV | 11.2 | |
| 4 | 16 KV | 11.2 | |
| 5 | 8 KV | 11.2 | |
| KLYSTRON BODY | 40 KV | 3.2 | 1% |
| MOD ANODE | 20 KV | | 1% |
| CATHODE HEATER | 20 V | 0.1 | 10% |
| SOLENOID | 20 V | 0.5 | 10% |
| COMPUTER | 20 V | 0.1 | 10% |
| RETROELECT | 20 V | 0.1 | 10% |
| TOTAL | | 59.8 | |

Figure B-1. PDS Simplified Block Diagram

⑦ 200 kW, dc/ac/dc power conditioner for dc motor drive, 600-900 volt dc input

⑧ 1.44 GW, dc high voltage transmission link, 800 kV, 1800 amp.



| ID | SUPPLIER | SIZE (WATTS) | SPECIFIC WEIGHT (KG/KW) | COMMENT |
|---|---|---|---|---|
| ① | AUTONETICS | 37 | 1.216 | STRIPPEG DOWN |
| ② | AUTONETICS | 250 | 1.268 | LOW VOLTAGE INPUT |
| ③ | TOPAZ ELECTRONICS | 1200 | 18.815 | |
| ④ | AEG TELEFUNKIN | 1500 | 1.4 | (INVERTER) |
| ⑤ | TRW | 2400 | 9.438 | |
| ⑥ | TRW | 25,000 | 1.268 | EXTRAPOLATED |
| ⑦ | AIRESEARCH | 200,000 | N/A | GRD RAPID TRANSIT |
| ⑧ | GE | 1.44 GW | N/A | GRD DC LINK |

*Figure B-2. Current dc Converter Technology Status*

The dc/dc converter complement is based on todays state of the art (SOA) technology. The complement is referenced to the TRW dc/dc converter operating at 25 kHz, utilizing heat pipe cooling. The weight allocation of the system components are:

| | |
|---|---|
| Magnetics | |
| Transformers | 25% |
| Inductors | 10% |
| Semiconductors & Mtg. | 20% |
| Cooling System | 30% |
| Mechanical | 15% |
| Total | 100% |

A projection of technology gain such as (1) increase in operating frequency, (2) increase in efficiency, (3) reduction in cooling system requirements, etc., is made in Figure B-3 and the equivalent size and weight reduction calculated. The weights are then normalized and a second, independent technology gain is projected. Multiple improvements may be projected in this manner.

250 KW MODULES (BASIS FOR ANALYSIS)

1978 PROJECT 0.96 KG/KW (FROM TODAY'S S.O.A.)
200-400 VDC SEMICONDUCTORS AVAILABLE
25 KHz SWITCHING CONVERTERS
HEAT PIPE COOLING
$\eta$ = 95%

1983 50 KHz ⇒ .9214 KG/KW BY TRANSFORMER FREQUENCY CHANGE
RECONFIGURE TO USE HALF AS MANY TRANSFORMERS ⇒ .8206 KG/KW *
INDUCTOR REDUCTION FOR FREQUENCY CHANGE = .8074 KG/KW
REDUCTION OF COOLING SYSTEM O.A. EFFICIENCY 95.5% = .7832 KG/KW
SEMICONDUCTOR HIGHER VOLTAGE RATINGS, IMPROVED POWER GAIN
& COMPLEMENTARY HIGH EFFICIENCY DRIVE TECHNIQUES = .7575 KG/KW
100 KHz = .7069 KG/KW

1988 IMPROVED POWER SEMICONDUCTORS (TRANSISTORS, SCR'S, POWER FETS)
INCREASED TRANSFORMER & INDUCTOR PERFORMANCE
(NEW CORE MAT'LS, NEW CONDUCTOR & INSULATION TECHNIQUES)
$\eta_{OA}$ = 97%
$W_p$ = 0.5 KG/KW

* NOTE: XFMRS ~ 23.7% OF DC CONVERTER WEIGHT

*Figure B-3. Basis for Technology Projections dc/dc Converters*

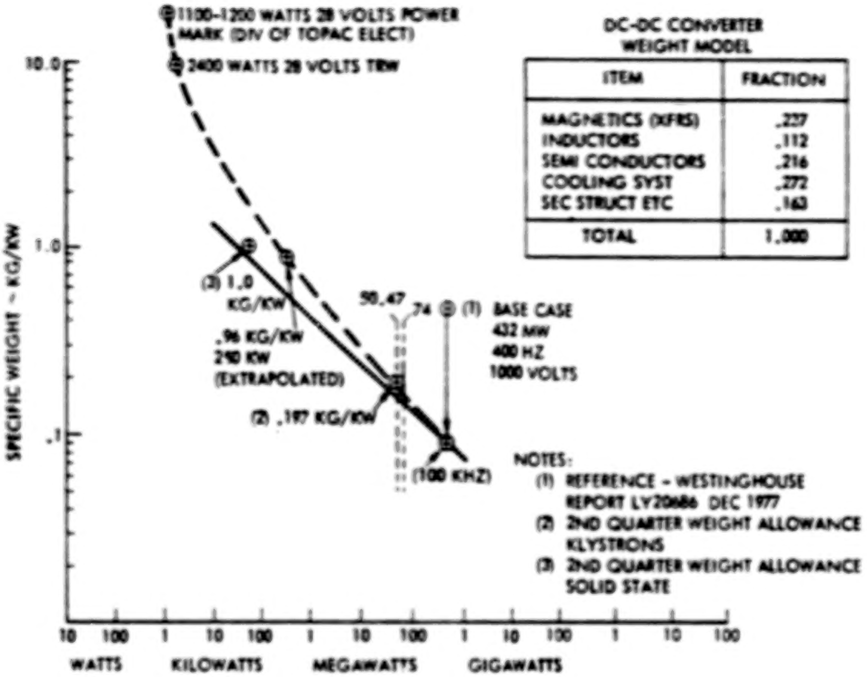
Figure B-4 shows the composite specific weight projections that were made to establish the dc power converter masses. The curve shows specific weight as a function of dc converter rating. The base case (point 1) was provided by Westinghouse. This data is corrected for 100 kHz frequency and a scaling relationship used to establish the solid curve $\left(\frac{Po}{P}\right)^{.75}$. The dashed curve was established by taking existing dc converter weights and by analysis projecting to 250 kW size at 0.96 kg/kW. This projection was extrapolated to the 100 kHz base case. The present Rockwell mass statement is based on 0.197 kg/kW utilizing the dc-dc converter weight model shown in the upper right corner.

Figure B-5 shows the dc converter requirements and weight impact comparisons for specific weights estimated as 1988 weights (i.e., compared to using the extrapolated 0.197 kg/kW SPS weight goals). The weight impacts on each element of the power distribution subsystem is tabulated for direct comparison to the point design and to show various configuration options including elimination of dc-dc conversion requirements by dedicated solar array voltages. The total weight impact varies between $0.422 \times 10^6$ kg and $3.576 \times 10^6$ kg penalty when using the higher converter specific weights.

## B.2 TECHNOLOGY ADVANCEMENT GOALS

Technology goals have been identified for the early experimental research period of 1979-1981 and ground and space demonstrations of 1981-1988.

The two major goals defined for the power distribution subsystem technology advancement for the early time period (1979-1981) are listed in Figure B-6. The first of these two goals deal with the dc converters technology investigations of approaches for dc converters which will allow an extension of current weight projections from 0.5 kg/kW to 0.197 kg/kW. The second goal is to validate a switchgear concept in terms of space application to achieve weight, efficiency and size as required for the SPS.



DC-DC CONVERTER WEIGHT MODEL

| ITEM | FRACTION |
|---|---|
| MAGNETICS (XFRS) | .227 |
| INDUCTORS | .112 |
| SEMI CONDUCTORS | .216 |
| COOLING SYST | .272 |
| SEC STRUCT ETC | .163 |
| TOTAL | 1.000 |

NOTES:
(1) REFERENCE - WESTINGHOUSE REPORT LY20686 DEC 1977
(2) 2ND QUARTER WEIGHT ALLOWANCE KLYSTRONS
(3) 2ND QUARTER WEIGHT ALLOWANCE SOLID STATE

Figure B-4. Dc-dc Converter Specific Weight Projections

WEIGHT IMPACT COMPARISONS ( $10^6$ KG)

| ITEM | REF WT | 1988 WTS → | CONFIGURATION OPTIONS | | |
|---|---|---|---|---|---|
| | | | 40 KV DIRECT | 40 KV, 32 KV DIRECT | ALL KLYSTRON VOLT DIRECT |
| MAIN CONDUCTORS | 1.902 | 1.902 | 1.902 | 1.928 | 3.345 |
| HV CONVERT | 1.74 | 4.413 | 3.229 | 2.422 | - |
| LV CONVERT | .222 | .468 | .468 | .468 | .468 |
| REGULATORS | .048 | .238 | .238 | .238 | .238 |
| SLIP RINGS | .043 | .043 | .043 | .086 | .215 |
| BRUSHES | .017 | .017 | .017 | .084 | .085 |
| SUBTOTAL | 3.929 | 7.081 | 5.897 | 5.176 | 4.351 |

NOTE: REF WT REDUCES TO 3.505 (40 KV DIRECT)

REQMTS

| VOLTAGE | POWER | QUANT | SP WT KG/KW | |
|---|---|---|---|---|
| | | | * | ** |
| 40 KV<br>32<br>24<br>16<br>8 | 74 MW<br>50.47 MW<br>-<br>-<br>- | 32<br>-<br>-<br>-<br>- | .1971<br>-<br>-<br>-<br>- | .5<br>-<br>-<br>-<br>- |
| LV | .2 KW<br>1.62 KW | 8,547<br>135,864 | 1<br>1 | 3.4<br>2.1 |
| REGULATORS ±1% | 3.5 KW | 135,864 | .1 | .5 |

*REFERENCE WEIGHTS - 2ND QUARTERLY
**EST. 1988 WEIGHTS

Figure B-5. Technology Weight Impacts (dc-dc Converter)

**1979 - 1981**

- INVESTIGATE NON-MAGNETIC (UNIQUE COUPLING) APPROACH FOR DC CONVERTERS

ELIMINATE TRANSFORMERS AND FROM EXPERIMENTAL RESULTS EXTEND WEIGHT PROJECTION FROM 0.5 KG/KW TO 0.197 KG/KW

- DEMONSTRATE VALIDITY OF CROSSFIELD DISCHARGE TUBE SWITCH GEAR CONCEPT

VERIFY WEIGHT (.00682 KG/KW), EFFICIENCY (99.9%) AND SIZE (6 MW TO 312 MW)

*Figure B-6. Technology Advancement Goals - 1979 to 1981 (Power Distribution Subsystem)*

Ground development program goals for 1981 to 1988 to advance the power distribution subsystem technology for dc converters are summarized in Figure B-7.

**DC CONVERTERS**

- DEMONSTRATE HIGH VOLTAGE (8000–32000 VOLTS) AND FREQUENCY (20 KHZ–100 KHZ) TECHNOLOGY
  10–250 KW
  ≤0.5 KG/KW

- INCREASE FREQUENCY 20 KHZ TO 100 KHZ
- REDUCE MAGNETICS
- INCREASE EFFICIENCY (TO 97%)
- REDUCE COOLING REQMT
- DEVELOP NEW MAGNETIC MAT'LS (OR ELIMINATE)

- DETERMINE SCALING RELATIONSHIPS
  WEIGHT FREQUENCY, VOLTAGE, AND POWER LEVEL

- TRANSFORMERS
- INDUCTORS
- SEMICONDUCTORS
- COOLING
- SECONDARY STRUCTURE

- DEVELOP EARLY VERIFICATION HARDWARE
  GEO SAT ~ 100 KW @ ≤1.0 KG/KW
- DESIGN SPS HARDWARE
  FEASIBILITY & PRELIMINARY DESIGN

- 100 KW TO 275 MEGAWATTS
- 8000–32000 VOLTS
- 100–200 KHZ
- ≤0.197 KG/KW

*Figure B-7. Technology Advancement Goals - 1981 to 1988 (Power Distribution Subsystem)*

There are four major goals identified:

1. Demonstrate high voltage (8000 - 32000 Volts) and frequency (80 kHz - 100 kHz). This goal involves technology advancements to achieve ≤ 0.5 kg/kW at sizes of 10 - 250 kW.

2. Determine scaling relationships: weight, frequency, voltage, and power level. The major dc converter weight items are identified as transformers, inductors, semiconductors, cooling and secondary structure. The SPS requirements are in the 50 megawatt size range and scaling relationships must be established from experimental data for SPS dc converter design.

3. Develop early verification hardware GEOSAT ~ 100 kW @ ≤ 1.0 kg/kW.

4. Design SPS hardware feasibility and preliminary design.

Figure B-8 lists technology advancements required for the power distribution subsystem. DC switchgear electromechanical devices physically interrupts the current by separating metallic contacts. Dc voltages over 50 volts establish arcs between the metal contacts. The higher the voltage the greater the arc problem. Verifications of methods to supress the arc is required. Solid state devices avoid arcing and introduce added losses - higher series voltage drops and do not supply galvanic isolation in off state. Solid state devices require great heat rejections. Conductor materials will be reviewed. Goal to be weight reduction. Means of terminating and connectors to be studied. Sliprings/brush technology for new materials for better conduction and less heat losses. A new commutation technique to be investigated.

SWITCH GEAR

- MAINTAIN SWITCHGEAR EFFICIENCY >99.9%
- IMPROVE WEIGHT GOAL > 0.0002 KG/KW
- DEVELOP CROSS FIELD TUBE FOR SPACE APPLICATION (BETTER HERMETIC SEALS, LOWER MAINTENANCE REQUIREMENTS, ETC.)
- VERIFY CYCLING LIFE FOR CROSS FIELD TUBE
- REDUCE SPUTTERING OF ELECTRODES
- DEVELOP LIGHTER WEIGHT NON-LINEAR RESISTORS
- INVESTIGATE SCR AND POWER TRANSISTORS FOR POWER SWITCHING

CONDUCTORS

- INVESTIGATE USE OF FIBER OPTICS - CONTROL CIRCUITS
- EXPLORE SUPERCONDUCTORS
- DEVELOP FLAT CONDUCTOR CONFIGURATION
- INVESTIGATE RIBBON TYPE CONNECTORS
- VERIFY CURRENT CARRYING CAPABILITIES OF FLAT CONDUCTOR
- CONFIGURATION

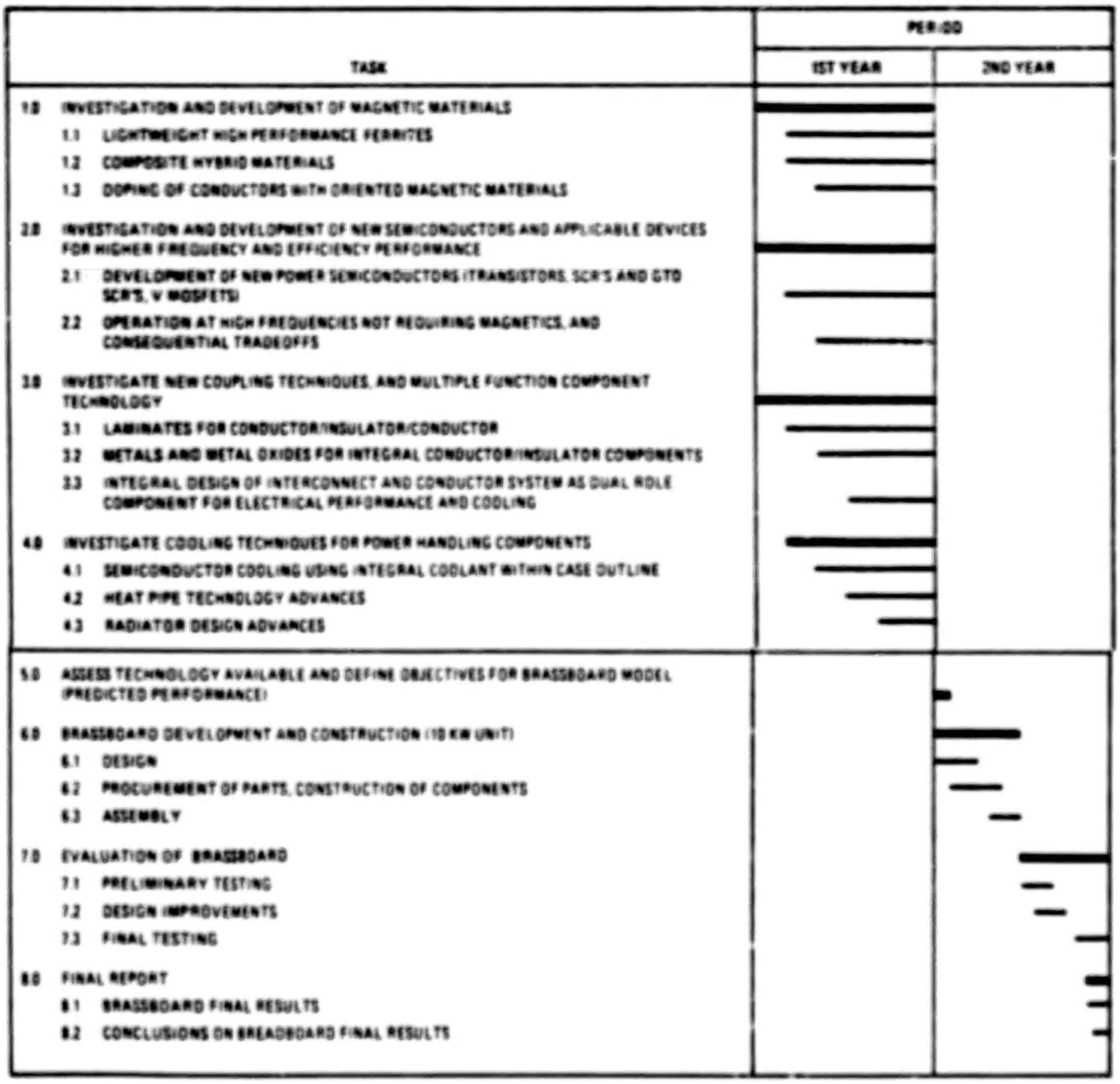
SLIP RINGS/BRUSHES

- INVESTIGATE NEW MATERIALS
- DEVELOP IMPROVED BRUSH CONDUCTION TO RINGS
- INVESTIGATE NEW ROTARY JOINT CONCEPTS, E.G., TWO DISKS WITH
- MERCURY COUPLING

*Figure B-8. Technology Advancement Requirements - 1981 to 1988 (Power Distribution Subsystem)*

## B.3 DC/DC CONVERTER DEVELOPMENT PROGRAM

Figure B-9 shows a proposed task statement and schedule for the early experimental research development of the dc converters. The first year deals with tasks 1 through 4 and involve investigation of magnetic materials, new semiconductors for higher frequency, new coupling techniques and cooling techniques. From these investigations it is expected that basic design approaches will be developed to meet the SPS dc converter weight goals of 0.197 kg/kW. The second year of effort is devoted to brassboard development and evaluation. From this comes the SPS dc converter design approach.



1.0 INVESTIGATION AND DEVELOPMENT OF MAGNETIC MATERIALS
  1.1 LIGHTWEIGHT HIGH PERFORMANCE FERRITES
  1.2 COMPOSITE HYBRID MATERIALS
  1.3 DOPING OF CONDUCTORS WITH ORIENTED MAGNETIC MATERIALS

2.0 INVESTIGATION AND DEVELOPMENT OF NEW SEMICONDUCTORS AND APPLICABLE DEVICES FOR HIGHER FREQUENCY AND EFFICIENCY PERFORMANCE
  2.1 DEVELOPMENT OF NEW POWER SEMICONDUCTORS (TRANSISTORS, SCR'S AND GTO SCR'S, V MOSFETS)
  2.2 OPERATION AT HIGH FREQUENCIES NOT REQUIRING MAGNETICS, AND CONSEQUENTIAL TRADEOFFS

3.0 INVESTIGATE NEW COUPLING TECHNIQUES, AND MULTIPLE FUNCTION COMPONENT TECHNOLOGY
  3.1 LAMINATES FOR CONDUCTOR/INSULATOR/CONDUCTOR
  3.2 METALS AND METAL OXIDES FOR INTEGRAL CONDUCTOR/INSULATOR COMPONENTS
  3.3 INTEGRAL DESIGN OF INTERCONNECT AND CONDUCTOR SYSTEM AS DUAL ROLE COMPONENT FOR ELECTRICAL PERFORMANCE AND COOLING

4.0 INVESTIGATE COOLING TECHNIQUES FOR POWER HANDLING COMPONENTS
  4.1 SEMICONDUCTOR COOLING USING INTEGRAL COOLANT WITHIN CASE OUTLINE
  4.2 HEAT PIPE TECHNOLOGY ADVANCES
  4.3 RADIATOR DESIGN ADVANCES

5.0 ASSESS TECHNOLOGY AVAILABLE AND DEFINE OBJECTIVES FOR BRASSBOARD MODEL (PREDICTED PERFORMANCE)

6.0 BRASSBOARD DEVELOPMENT AND CONSTRUCTION (10 KW UNIT)
  6.1 DESIGN
  6.2 PROCUREMENT OF PARTS, CONSTRUCTION OF COMPONENTS
  6.3 ASSEMBLY

7.0 EVALUATION OF BRASSBOARD
  7.1 PRELIMINARY TESTING
  7.2 DESIGN IMPROVEMENTS
  7.3 FINAL TESTING

8.0 FINAL REPORT
  8.1 BRASSBOARD FINAL RESULTS
  8.2 CONCLUSIONS ON BREADBOARD FINAL RESULTS

*Figure B-9. Dc/dc Converter Development Program*

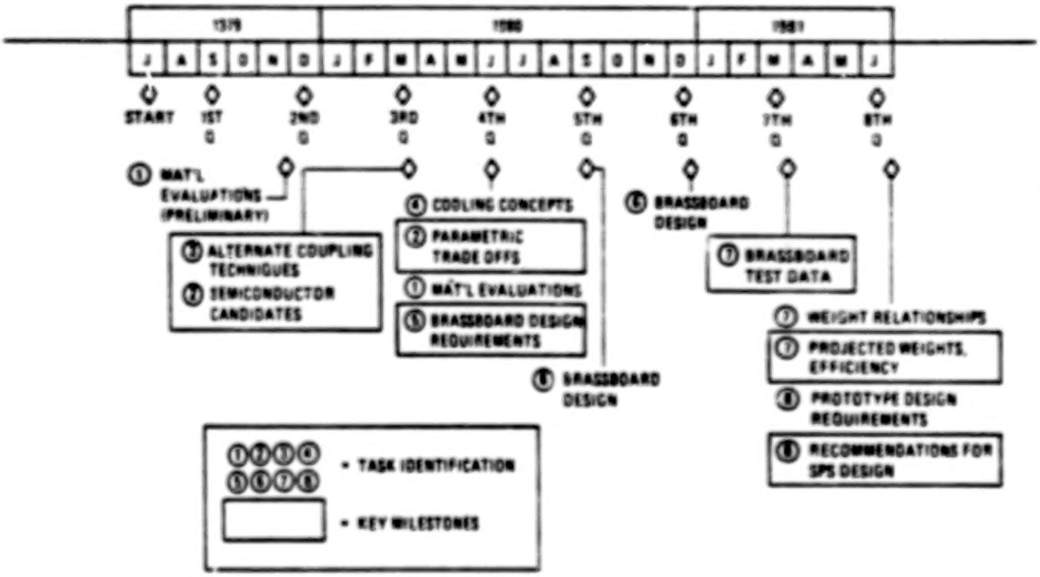
A detailed milestone/schedule for the early experimental research period is shown in Figure B-10. The major milestones are indicated with the associated task identified. The following major milestones are shown:

3rd Quarter - Alternate Coupling Techniques (Task 3)
Semiconductor Candidates (Task 2)

4th Quarter - Parametric Trade Offs (Task 2)
Brassboard Design Requirements (Task 5)

7th Quarter - Brassboard Test Data (Task 7)

8th Quarter - Projected Weights, Efficiencies (Task 7)
Recommendations for SPS Design (Task 8)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2ND Q
3RD Q
4TH Q
5TH Q
6TH Q
7TH Q
8TH Q
① MAT'L EVALUATIONS (PRELIMINARY)
③ ALTERNATE COUPLING TECHNIQUES
② SEMICONDUCTOR CANDIDATES
④ COOLING CONCEPTS
② PARAMETRIC TRADE OFFS
① MAT'L EVALUATIONS
⑤ BRASSBOARD DESIGN REQUIREMENTS
⑥ BRASSBOARD DESIGN
⑥ BRASSBOARD DESIGN
⑦ BRASSBOARD TEST DATA
⑦ WEIGHT RELATIONSHIPS
⑦ PROJECTED WEIGHTS, EFFICIENCY
⑧ PROTOTYPE DESIGN REQUIREMENTS
⑧ RECOMMENDATIONS FOR SPS DESIGN
①②③④ ⑤⑥⑦⑧ - TASK IDENTIFICATION
- KEY MILESTONES

*Figure B-10. Dc Converter Milestones*

## B.4 SWITCHGEAR TECHNOLOGY DEVELOPMENT

An industry survey was performed to obtain information pertaining to high dc voltage switchgear. Figure B-11 outlines the options to date. Arc suppression across the metallic switch contacts of switchgear for dc voltages above 50 volts is the principal problem. Various methods have been studied and experimented with. Solid state devices, i.e., power transistors and SCR's used in various combinations are being investigated. These devices have no arcing problems. A development program to extend the state-of-art to high dc voltages (40 kV range) does not seem to encouraging. Electromechanical switches of various design concepts seem the most plausible approach. The cross field discharge tube application appears to be a viable approach to meet or better the design goals for weight and efficiency.

TWO OPTIONS

- FORCED COMMUTATION - SOLID STATE OR MECHANICAL BREAKERS
- CROSS FIELD INTERRUPTORS - MECHANICAL BREAKERS

FORCED COMMUTATION

PRECHARGED CAPACITOR BANK AND L-C CIRCUIT WITH THYRISTOR STRINGS OR IGNITIONS (PROVIDES CURRENT PULSE IN EXCESS OF CURRENT TO BE INTERRUPTED)

CROSS FIELD (PENNING) DISCHARGE TUBE

MAGNETIC FIELD TUBE AND NON-LINEAR RESISTOR COMPONENTS (ARC VOLTAGE DRIVES TUBE TO CREATE IONIZATION (PLASMA) PATH FOR CURRENT FLOW WITH ENERGY STORAGE DEVICE)

NOTE: BASELINE SELECTION IS CROSS FIELD (PENNING) WITH WEIGHT GOAL 0.00682 KG/KW AND EFFICIENCY OF 99.9%

- WEIGHT GOAL APPEARS ACHIEVEABLE
  HUGHES (MALIBU RESEARCH LAB) CONCURS BASED ON GROUND EQUIPMENT
  WESTINGHOUSE PROJECTS ORDER OF MAGNITUDE BETTER
- SPS CONCEPT IS VERY SENSITIVE TO SWITCHGEAR EFFICIENCY

*Figure B-11. Switchgear Concepts*

Figure B-12 shows where the Hughes crossed field technique has been applied in high dc voltage applications. At the Culham Laboratory the crossed-field interrupter is to give fast high voltage protection of an injector system. The interrupter was stressed to 150 kV dc on a low level interruption test and installed for testing 120 kV/2-4 mW dc supply connection to the injector test line. Both tasks were successful. Electric Power Research Institute successfully tested the crossed-field interruptor at the Sylmar Substation as a circuit breaker on the pacific HV dc intertie. The crossed-field interruptor is installed on a high voltage ac for current limiting to test its capabilities for interruption ac power. The crossed-field tube is being installed at Northern Terminal Pacific Intertie as a transfer breaker in a metal return interrupter.

| CUSTOMER | APPLICATION | VOLTAGE | CURRENT | POWER |
|---|---|---|---|---|
| CULHAM LABORATORY ABINGDON UK | HIGH VOLTAGE SERIES PROTECTION OF A MEGAWATT NEUTRAL INJECTOR IN OPERATION 8 MONTHS | 120 KV | 40A | 4.8 MW |
| ELECTRIC POWER RESEARCH INSTITUTE PALO ALTO, CA | HIGH VOLTAGE D.C. CIRCUIT BREAKER DEVELOPED FOR POWER SYSTEM EQUIPMENT SUPPORTED BY THE NATIONS ELECTRIC UTILITIES TESTED AT SYLMAR SUCCESSFULLY. | 92 KV | 620A | 57.04 MW |
| AMERICAN ELECTRIC POWER SERVICE CORP N.Y., N.Y | INSTALLED MUSKINGUM RIVER, OHIO A.C. CURRENT LIMITING IN 9-78 (EXPERIMENTAL TESTING) | (A.C.) 138 KV RMS | 4000A | 552 MW |
| ELECTRIC POWER RESEARCH INSTITUTE,PALO ALTO, CA | BEING INSTALLED AT CELILO. NORTHERN TERMINAL PACIFIC HV-D.C. INTERTIE METALLIC RETURN TRANSFER BREAKER | 80 KV | 1000A | 80 MW |

*Figure B-12. Hughes Research Laboratories Crossed-field Interrupter Developments*

Figure B-13 outlines a study-design program to investigate and make an analysis of the criteria required to design a high dc voltage switchgear for use in space and to meet or better the weight goal of 0.00682 kg/kW and an efficiency of 99.9%. Several candidate switchgear mechanism will be reviewed and analyzed in light of the following criteria at various current ratings: weight, basic electric characteristics, dielectric withstand, efficiency, reliability review, control requirements and service life. A verification of the preliminary design will be done by using available Hughes test hardware: cross-field interruptor (XFT), and mechanical transfer switches operating in tandem. The hardware will be assembled and instrumented to evaluate steady state conduction of composite interruptor in "closed state"; transfer test followed by dc interruption; steady state dielectric tests, transient recovery tests, and limited fault current tests. After compilation off an analysis of test results it should be able to evaluate the various trade-offs available in system performance cost and reliability. This will provide a firm basis for design of the "brassboard" switchgear. Embodyment of the above analytical and development test efforts it is planned to design, fabricate test and demonstrate a high dc voltage switchgear. The "brassboard" will be at "black box level", i.e., two terminal level and will be tested for compliance to weight, size, conformance, auxiliary power subsystem, and mechanical integrity. These results would be demonstrated and a comprehensive test report would be prepared and submitted.

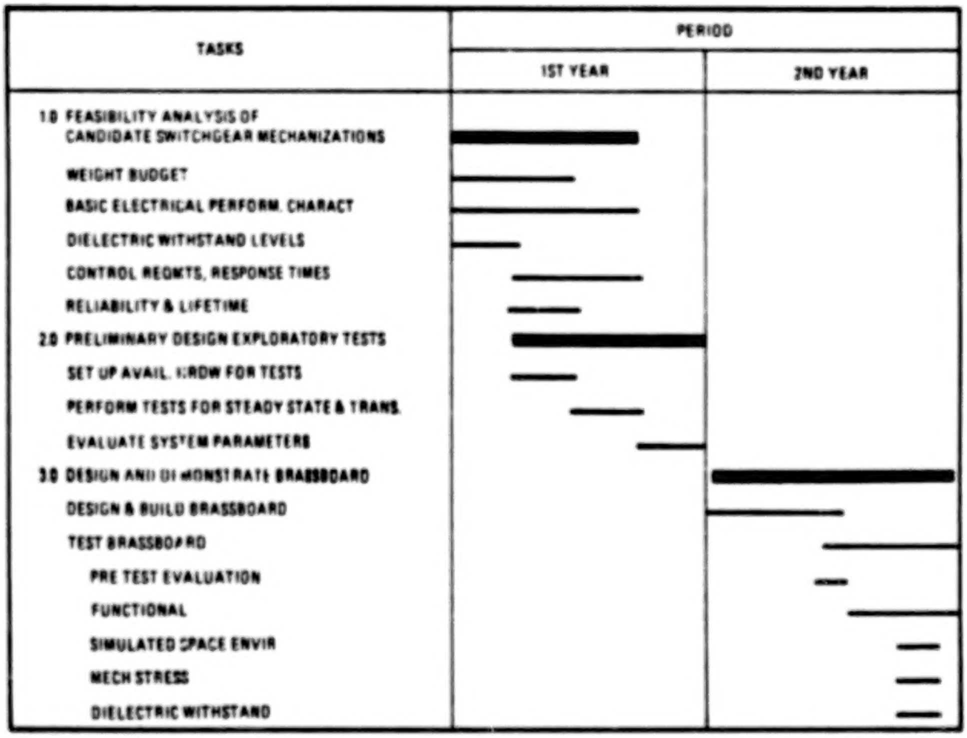

*Figure B-13. Switchgear Development Program Schedule Early Exploratory*

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15. Supplementary Notes

Marshall Technical Monitor: C. H. Guttman
Volume III of Final Report

16. Abstract

Recently, DOE has proposed, for FY 1980 implementation, a modest environmentally-oriented microwave technology exploratory research program aimed at reducing the uncertainty associated with microwave power system critical technical issues. These factors lead to the underlying premise that heavily funded, dedicated SPS development effort during the next five years or so is increasingly unlikely, and that a low-level step-by-step evolutionary approach to SPS development planning is realistic. This premise then dictates a planning logic that builds upon on-going and planned ground and space test activities--activities that can result in cost-effective SPS developmental progress if they can be focused to achieve significant advancement of SPS technology while also providing other planned benefits.

Based upon this background, an evolutionary SPS development plan was prepared. Planning analysis was directed toward the evolution of a scenario that met the stated objectives, was technically possible and economically attractive, and took into account constraining considerations, such as (1) requirements for very large-scale end-to-end demonstration in a compressed time frame, (2) the relative cost/technical merits of ground testing versus space testing, and (3) the need for large mass flow capability to LEO and GEO at reasonable cost per pound.

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